THE
JOURNAL OF GEOLOGY

A SEMI-QUARTERLY

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VOLUME XLIII

JANUARY–DECEMBER, 1935

R550 1935 v.43

THE UNIVERSITY OF CHICAGO PRESS
CHICAGO, ILLINOIS

THE CAMBRIDGE UNIVERSITY PRESS, LONDON
THE MARUZEN COMPANY, LIMITED, TOKYO
THE COMMERCIAL PRESS, LIMITED, SHANGHAI

MAR 2 1936

PUBLISHED FEBRUARY, MARCH, MAY, JUNE, AUGUST, SEPTEMBER,
NOVEMBER, DECEMBER, 1935

COMPOSED AND PRINTED BY THE UNIVERSITY OF CHICAGO
PRESS, CHICAGO, ILLINOIS, U.S.A.

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VOLUME XLIII NUMBER 1

THE
JOURNAL OF GEOLOGY

January-February 1935

MIGMATITES OF THE SAWATCH RANGE, COLORADO

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Northwestern University

ABSTRACT

The crystalline core of the Sawatch Range is composed of coarse schist and gneiss, largely of sedimentary origin. Two distinct periods of batholithic intrusions occurred in pre-Cambrian time. Wide zones of mixed supercrustal and granitic material border the outcrops of the batholiths and show gradational facies on one side into the sedimentary schists and on the other side into the plutonic rocks. From field relations and microscopic study of thin sections these migmatite zones are interpreted as being due to regional granitization or replacement, involving the carrying out and bringing in of material by emanations, gaseous or liquid, from the invading batholiths.

INTRODUCTION

To certain confusing mixtures of supercrustal and granite material—schists, basic eruptives and granites—Sederholm has applied the term "migmatites."[1] Rocks of this type characterize zones bordering pre-Cambrian batholithic intrusions of the Sawatch Range in central Colorado and show over wide areas the effects of rock mixing at great depth. Whether the mixing is due wholly to viscous intrusion, magmatic differentiation, and recrystallization of the intruded host rocks, or whether replacement has played any important rôle in converting areas of schists and gneisses into granitic migmatites *in situ*, has long been a matter of controversy. It is with these opposing

[1] J. J. Sederholm, "On Migmatites and Associated Pre-Cambrian Rocks of Southwestern Finland," *Comm. geol. Findlande Bull.* No. LVIII (1923), p. 14.

points of view in mind that the present study of the origin of the Sawatch schists has been made.

An excellent summary of the literature and growth of the ideas of regional granitization by replacement as opposed to the older ideas of little or no transference of material from granitic contacts is given by Sederholm in the memoir on migmatites.[2] Since then numerous articles have appeared supporting some form of replacement in zones of mixed rocks. Gilluly's recent paper on the replacement of an albite granite[3] contains a good bibliography on the subject with special attention given to the foreign literature.

GENERAL GEOLOGY OF THE SAWATCH RANGE

The main topographic features of central Colorado consist of two nearly parallel mountain belts separated by a series of broad intermontane basins, the familiar North, Middle, and South parks. The western belt is composed of several more or less disconnected ranges of which the Sawatch is one of the most prominent. It extends south from the structurally depressed valley of the Eagle River to the valley of Tomichi Creek. The broad valley of the Arkansas River parallels the eastern side of the range for most of its length. Mount of the Holy Cross in the northern part of the range is approximately 100 miles southwest of Denver and Mount Princeton in the southern part is 80 miles due west of Colorado Springs (Fig. 1).

The Continental Divide follows the Sawatch Range over two-thirds of its length of 80 miles, and many crests rise above 14,000 feet. Glacial effects have been profound, leaving only a few of the highest peaks to rise above the ice-eroded slopes and encroaching cirque heads.

The range for the most part is composed of coarse crystalline schist and gneiss with at least two distinct periods of plutonic invasions in pre-Cambrian time—the older Pikes Peak and the later Silver Plume batholiths. On both sides of the range Paleozoic sediments dip away from the crystalline core. These formations range from the unconformable Cambrian quartzite at the base through Ordovician, De-

[2] *Ibid.*, pp. 1–21.

[3] James Gilluly, "Replacement Origin of an Albite Granite near Sparta, Oregon," *U.S. Geol. Surv. Prof. Paper 175-c* (1933), pp. 65–81.

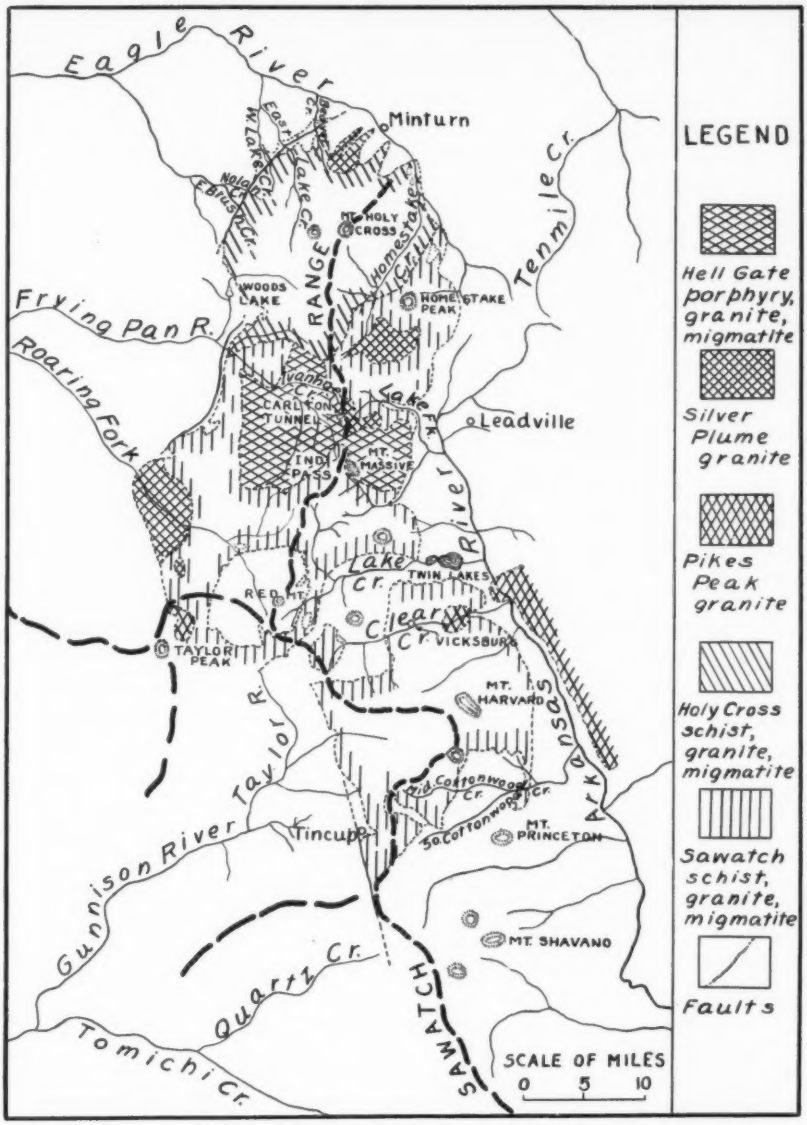


FIG. 1.—Sketch map showing location of Sawatch Range and the general relationships of the pre-Cambrian intrusions to the migmatized schists.

vonian, and Mississippian limestones, sandstones, and shales into the Red Beds of Permo Carboniferous age. The strike of the upturned sediments roughly parallels the present northward trend of the range and in this respect the structure corresponds to the simple anticlinal doming of the Laramide revolution described by early writers.[4] Low-angle thrust faults are recognized in the sediments bordering the flanks of the range. The pre-Cambrian formations possess an earlier structure which, in the northern and central parts of the range, is nearly at right angles to the present trend of the range and consists of closely compressed, overturned, isoclinal folds with axial planes dipping steeply to the northwest with a regional trend of N. 60°–65° E.[5] In the southern part of the range this trend swings through north to northwest.

In Tertiary time the southern portion of the range was intruded by the Princeton batholith. Numerous stocks, sill, dikes, and flows occur throughout the region and are thought to be related in age to the Tertiary intrusive.

THE PRE-CAMBRIAN SCHISTS[6]

Many types of schists are represented in the pre-Cambrian crystallines, but for a large majority of the formations a sedimentary origin is evident. This is shown by numerous lenses of quartzite, graywacke, and cherty limestone which are common in most sections, and locally by large areas of quartzite and crystalline limestone and marble which are conformable with, and grade into, the schists. In a few areas, such as the valleys of Ivanhoe, Homestake, Roaring Fork, Cottonwood, and Nolan creeks and their tributaries, black hornblende schists show irregular relationships to the more quartzose and feldspathic schists suggesting an origin from basic intrusives. Chloritic greenstone occurs in a few places, notably north of Wood Lake

[4] A. C. Peale, *U.S. Geol. and Geog. Surv. Terr. Ann. Rept. for 1873*, Pt. I (1874), p. 246; F. V. Hayden, *ibid.*, pp. 39, 49.

[5] J. T. Stark and F. F. Barnes, "The Structure of the Sawatch Range," *Amer. Jour. Sci.*, 5th ser., Vol. XXIV (1932), p. 475.

[6] The term "Schist" is used here in a general sense to include both the finely foliated and coarsely gneissic schistose rocks. In many outcrops the rocks might be called either gneissic schists or schistose gneiss, and these are so intimately mingled that areal distributions cannot be shown on the ordinary map.

and south of Tincup Pass, but in general the schists consist largely of quartz and feldspar with local facies rich in biotite, garnet, sillimanite, and hornblende.

Throughout the range the schists have been intimately intruded by lit-par-lit stringers, sills, and stock-like masses from the Pikes Peak, Silver Plume, and Princeton batholiths. Different facies of the schistose formations grade irregularly into each other and appear more commonly due to metamorphic effects of igneous intrusion than to original differences in composition.

THE PRE-CAMBRIAN INTRUSIVES

In the following discussion the Pikes Peak and Silver Plume batholiths are treated as separate invasions. In other areas granite of the Silver Plume type has been found cutting the Pikes Peak granite[7] and the general appearance of large outcrops of the latter suggests its older age. But each of the batholiths exhibits several facies ranging from quartz monzonite to true granite, and in isolated outcrops it is difficult to tell to which batholith the rock belongs. It does not seem unreasonable, in view of the striking lithologic similarity between many facies of the two granites, that both batholiths may represent different stages of a long-extended period of magmatic invasion and that probably no great break exists between the youngest of the Pikes Peak and the oldest of the Silver Plume facies, although the major intrusions of each type were undoubtedly separated by a very long time interval.

THE PIKES PEAK GRANITE

The oldest of the pre-Cambrian plutonites, the Pikes Peak, forms the gorge of the Arkansas River south from Granite and extends westward on to the flanks of the Sawatch Range along Clear Creek (Fig. 1). Glacial moraines and gravel terraces mask much of the bed rock at the mouth of the creek, which probably is underlain by granite. Farther west, streams heading into the divide have cut into a highly altered quartz monzonite. Similar rock is exposed 10 miles west of the divide. Both of these outcrops represent basic facies of the Pikes Peak granite, which is well exposed in the gorge of the

[7] S. H. Ball, "Geology of the Georgetown Quadrangle, Colorado," *U.S. Geol. Surv. Prof. Paper 63* (1908), pp. 46–60.

Arkansas River, and they may be connected with it below the surface. That these intrusions were rich in mineralizers is indicated by the wide gradational zones into the schists which show all degrees of porphyroblastic crystal development.

At Pikes Peak Mathews[8] recognized four main types of granite. The oldest of these, the Pikes Peak type, is strikingly similar to the Rosalie granite described by Ball[9] as the youngest of the older pre-Cambrian intrusions in the Georgetown quadrangle. The Rosalie granite cuts quartz monzonite which is associated with quartz-bearing diorite.[10] In the Sawatch Range the oldest plutonites correspond most nearly to the quartz monzonite and quartz-bearing diorite. They are characterized by relatively large porphyritic feldspars, commonly an inch or more in length, and less conspicuous quartz.

Under the microscope the fresher specimens show an even granular, hypidiomorphic texture. The feldspar varies from andesine to oligoclase with lesser amounts of microcline and antiperthite, both of which are later and suggest a deuteric origin. Other essential minerals in order of abundance are quartz and biotite. Accessory magnetite, titanite, apatite, pyrite, and zircon are present in all slides. The rock shows much evidence of shearing and alteration and the earlier feldspars exhibit all degrees of saussuritization. With the exception of the absence of hornblende, the rock is similar in many respects to the "older granites" of the Georgetown quadrangle.[11]

THE SILVER PLUME GRANITE

The younger pre-Cambrian massive, the Silver Plume granite, is represented in many areas throughout the range from the extreme southern portion to the northern limit. The exposures vary from a fraction of a mile to several miles square and are more numerous and stock-like near the center of the range. Large outcrops occur in the valleys of Lake Fork and Ivanhoe creeks, west of Leadville, on the divide north of Independence Pass, and in the Mount of the Holy Cross region. In many of these localities accordant stringers and sills of pink and white pegmatite cut the schists and are traceable to

[8] E. B. Mathews, "The Granitic Rocks of the Pikes Peak Quadrangle," *Jour. Geol.*, Vol. VIII (1900), pp. 214–40.

[9] *Op. cit.*, pp. 57–60. [10] *Ibid.*, p. 56. [11] *Ibid.*, pp. 45–57.

larger stock-like masses. The pegmatite intrusions increase in thickness and number as the range crests are approached, finally breaking through and engulfing large masses of the host rock.

A later series of pegmatites follows in part the old lines of weakness, paralleling schistosity and bedding, but more commonly cutting across the bedding and earlier sills (Fig. 2). All of the pegmatitic material is lithologically similar to the Silver Plume granite and is

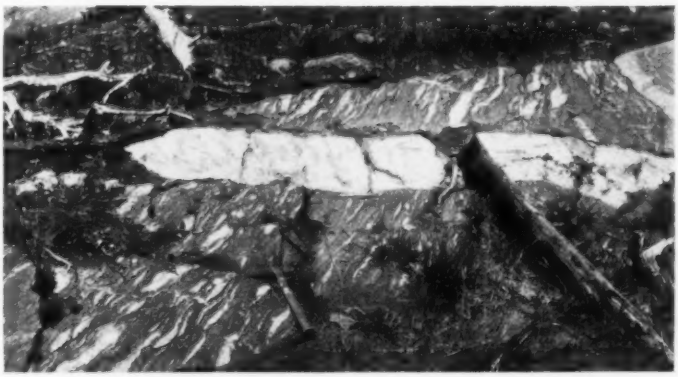


FIG. 2.—Early lit-par-lit intrusions of Silver Plume pegmatite cut by later pegmatite, pre-Cambrian schist near Homestake Lake.

believed to represent late phases of the Silver Plume invasion. A few lamprophyres are associated with the youngest pegmatites.

This intrusion of the schists in such intimate fashion—lit-par-lit throughout all parts of the range—suggests a stromatolithic[12] type of batholithic invasion. Areas of schist surrounded by granite appear to be roof pendants. Much of the range is believed to be underlain by the Silver Plume massive, with roof cupolas here and there projecting through the overlying schists. The probable nearness of the granite to the present surface would explain the wide zones of migmatized schist which not only border the cupolas but occur for miles along the flanks of the range.

In the type area the Silver Plume plutonite is described as a mas-

[12] W. G. Foye, "Are the Batholiths of the Halliburton-Bancroft Area, Ontario, Correctly Named?" *Jour. Geol.*, Vol. XXIV (1916), p. 791.

sive granite with porphyritic habit, marked by more or less idiomorphic feldspars.[13] In the Sawatch Range outcrops of the rock vary from fine to coarse textured granite with many gradations into pegmatite. Trachytoid feldspars are characteristic. Under the microscope the rock exhibits a hypidiomorphic texture varying from even granular to porphyritic. The feldspars are microcline, orthoclase, and oligoclase with many perthitic intergrowths, and in nearly all sections sericitization of the feldspars is well developed. Micropegmatite is commonly present but not abundant. Quartz, biotite, and muscovite are present in varying amounts, the latter becoming prominent in some of the coarser grained facies. Accessory minerals in order of abundance are magnetite, titanite, apatite, pyrite, and zircon. In the majority of the sections studied the proportion of the feldspars indicates a quartz monzonite.

The pegmatite dikes associated with the Silver Plume massive resemble it in composition, and gradational zones are common. The dikes are composed chiefly of white and pink feldspar, orthoclase, and microcline, much of which shows perthitic intergrowths. Quartz is prominent and in many places apparent gradations exist from the pegmatitic rock into quartz veins. Biotite and muscovite are abundant in some facies and almost entirely lacking in others. The accessory minerals are the same as those in the Silver Plume mass. Garnets are locally abundant and hornblende is present in some of the dikes.

MIGMATITE ZONES BORDERING THE PIKES PEAK GRANITE

The Pikes Peak granite can be traced from the gorge of the Arkansas River up the valley of Clear Creek for 6 miles, where it grades into a mixed zone of granitic material and biotite-chlorite schist. East of Vicksburg the rock might be described as either a schistose granite or a granitized schist, accordingly as one approached from the schist or the granite side.

In the immediate vicinity of Vicksburg, however, the rock is a dark massive schist conforming in lithology and structure to larger areas of schist farther west. All gradations from schist into schistose granite occur. Much of the schist is porphyroblastic in texture, show-

[13] Ball, *op. cit.*, pp. 58–59.

ing large crystalloblasts of pink feldspar and quartz, in a dark green, schistose ground mass. The crystalloblasts have developed along lines of schistosity as small lens-like pods less than a millimeter in diameter and from this size grade into almond-shaped lenses an inch or more in length. As the pods become larger they tend to lose their oval shape and assume rectangular outlines of true feldspar phenocrysts. Some of the larger crystalloblasts have biotite laminae curved

FIG. 3.—Clear Creek schist showing porphyroblasts of plagioclase and quartz in a schistose matrix of chlorite and biotite.

around them as though the growing feldspar had crowded aside the foliae of the schist. Other lenses are joined along schistose lines by fine thread-like stringers of quartzose and feldspathic material. Some of the pods may be broken out and appear to occur as completely isolated masses in the schistose matrix (Fig. 3). Many facies of the porphyroblastic schist resemble the ecolé injection phenomena described by Whitman.[14]

Pegmatite stringers and some irregular areas of granitic material occur and suggest directions along which solutions may have entered. These are, however, small in quantity throughout the mile-and-a-half section of the gradational porphyroblastic zone which is crowded

[14] A. R. Whitman, "A Syntectic Porphyry at Porcupine," *Jour. Geol.*, Vol. XXXV (1927), pp. 404–20.

with thickly spaced crystalloblasts of pink feldspar and quartz in closely spaced bands paralleling the schistosity (Fig. 3).

In the Clear Creek area the porphyroblastic schist seems clearly to have formed by the development of feldspar and quartz crystalloblasts in a massive schistose rock due to contact action of the Pikes Peak granite. Gaseous or hot liquid solutions, permeating along the schistosity, fed centers of crystallization until gradually a large portion of the schist was replaced by small lenses of feldspar and quartz. As these crystalloblasts grew larger some crowding aside of the schistose laminae accompanied the replacement, but in the majority of cases the biotite and chlorite laminae abut abruptly against the crystalloblasts.

In thin sections, under the microscope, the plagioclase (oligoclase-andesine) forms the largest and most abundant constituent. All grains show much saussuritization. The larger grains have a rude crystal outline, but nowhere are the boundaries sharp, the feldspar penetrating with irregular contacts in all directions the schistose matrix. Subsequent deformation accompanied by fracturing and recrystallization is evident. Smaller areas of microcline and perthitic feldspar occur along contacts and within the older plagioclase grains. Quartz, which is second in abundance to the feldspar, is the freshest mineral in the rock, though the microcline and perthite are apparently contemporaneous with it. The quartz occurs as aggregates of interlocking grains in stringer, lenses, almond-shaped pods, and disseminated grains throughout all the schist. Myrmekite areas occur throughout the schistose matrix (Fig. 9). So abundant in places are the feldspar and quartz that very little of the schistose groundmass remains. This matrix is now composed largely of biotite, pistacite, chlorite, magnetite, and remnants of highly altered feldspar. A few scattered areas of altered amphibole suggest that the biotite may have developed from hornblende and that the rock may have been a hornblende greenstone schist previous to the intrusion of the Pikes Peak granite.

Field relations, supported by evidence of thin sections under the microscope, leave little doubt as to the secondary nature of the large areas of quartz and feldspar. No one—so far as the writer knows—has questioned their origin being due to true porphyroblastic replacements in a schistose groundmass.

Between the Pikes Peak granite and the typical porphyroblastic schist there is a zone, the origin of which is not so clear. Here large crystals of pink feldspar and quartz occur in a schistose matrix of biotite and chlorite. Many of the feldspars are similar microscopically to the crystalloblasts in the schist, but they are also strikingly like the feldspar phenocrysts of the massive granite.

It is in such zones as this that differing field interpretations as to origin may easily arise. The following quotation from Marvine's early description of migmatitic rocks in the Middle Park region might be equally well applied to any of dozens of gradational contacts in the Sawatch Range.

> Indeed, there seemed cases where, in approaching the same mass of granite from different points, that at one all the appearances of a truly exotic and eruptive origin might be found—abrupt lines of demarkation and veins; while at another point, nearly all the steps of a gradual metamorphism and transition from the schists beyond might be traced, while remnants of structure through the mass itself would, in greater part, conform to the surrounding system of folds, showing it as a whole to be an indigenous mass. Two observers thus approaching such a mass would justly render different verdicts as to its nature, one ascribing it to a wholly eruptive origin, the other a clearly metamorphic character.[15]

A border zone of the intruding granite, contaminated by inclusions from the host rock with more or less assimilation, might account for the present mixed appearance of the gradational zones between the granite and schist. On the other hand, many of the large feldspars in the mixed zone are definitely later than the surrounding matrix and this, with the occurrence of the adjacent porphyroblastic schist, strongly suggests that their origin may be due to replacement and that the indefinite border zone represents a more thoroughly migmatized portion of the porphyroblastic schist into which it grades.

In this connection an outcrop of granite-like rock in the west wall of the valley of Lake Fork, a short distance south of Vicksburg, is illuminating. The rock appears to be a part of the quartz diorite facies of the Pikes Peak granite and was so considered until a weathered surface revealed the presence of well-rounded pebbles. Closer inspection disclosed a migmatized conglomerate in which the psephitic origin was apparent only in the highly weathered surface

[15] A. R. Marvine, *U.S. Geol. and Geog. Surv. Ter. Ann. Rept. for 1873* (1874), p. 143.

zone. The pebbles average from 1 to 3 inches in diameter and are composed of different types of schistose rocks. Throughout the rock the impregnation by granitic juices and development of large crystalloblasts of feldspar in the schistose matrix all but disguise the conglomeratic nature of the formation.

About other outcrops of the Pikes Peak granite in the Sawatch Range migmatized zones occur, but in no place is the gradational relationship so well exposed as at Clear Creek.

MIGMATIZED ZONES BORDERING THE SILVER PLUME GRANITE

In size and in number of outcrops the Silver Plume granite is the more important of the pre-Cambrian intrusions in the Sawatch Range. Like the Pikes Peak granite it was rich in mineralizers and the bordering zones, in which the granitic material is mixed intimately with the invaded schists, form a considerable part of the crystalline surface of the present core of the range.

One of the most accessible places to observe gradational zones between the Silver Plume granite and schist occurs west of the continental divide from Hell Gate on Ivanhoe Creek to Nast on Fryingpan River. The compound cirque at the head of the southwest fork of Lake Creek also shows a complete gradation from granite, through a wide mixed zone into porphyroblastic schist of sedimentary origin. On the north slope of Red Mountain, facing Taylor Peak, migmatization has been effected by the intruding Silver Plume massive. Large areas on the east slope of Mount Massive and along the divide from Carleton Pass north to Mount of the Holy Cross show migmatized schists suggestive of granite not far beneath the surface.

In the valleys of Beaver, East Lake, West Lake, and East Brush creeks, all in the northern part of the Sawatch Range, schists are exposed showing all degrees of granitic impregnation, lit-par-lit intrusions, and porphyroblastic replacements.

In most of these areas early lit-par-lit pegmatites cut schists, preceding in some places intrusions of the main Silver Plume mass. They are commonly followed by a later series of pegmatites cutting indiscriminately across the schist, granite, and mixed border zones between the two (Fig. 2).

Near Hell Gate outcrops of typical pink Silver Plume granite,

showing characteristic trachytoid alinement of idiomorphic feldspars, grade into streaked and banded granitic zones. Dark bands vary in width from several feet to thin shadow lines and are composed of

FIG. 4.—Hell Gate migmatite showing dark bands of porphyroblastic schist.

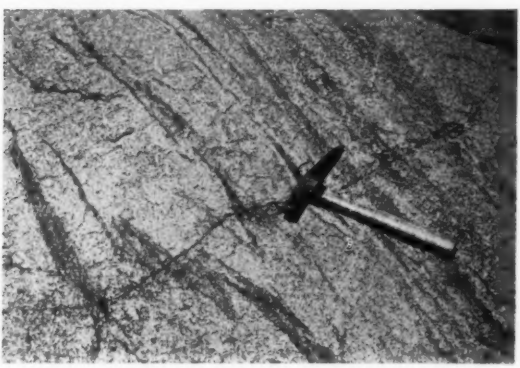


FIG. 5.—Hell Gate migmatite showing relict "ghosts" of schist

biotite-rich quartz feldspar schist (Figs. 4 and 5). Some of the more massive biotite-rich bands are recognizable as part of the adjacent crystalline schist into which the Silver Plume granite is intruded. The dark schist fades into pink granitic rock with a gradual increase of feldspar and quartz, apparently continuous with, and similar to,

that in the massive granite. These dark, thin lines—shadow streaks or ghosts—parallel the more massive schist bands and are composed of biotite laminae. Schistosity in the bands and shadows agrees in strike with the regional structure in adjacent schist areas. Thick bands fade out longitudinally as well as crosswise through gradations of fine shadow lines of biotite which suggest relic structures of a pre-existing schist in the granitic rock.

Adjacent to the banded rock are large areas which at first were thought to be a coarse-grained, porphyritic granite with pink feldspar crystals an inch or more in length. These show a rude but clearly discernible trachytoid alinement. If the rock was formed as a differentiation border, or was a late pegmatitic facies of the Silver Plume massive, the parallelism of the large feldspar crystals would be the result of primary flow of intrusion. Careful study of the outcrops, however, suggests a porphyroblastic origin for the large crystals. The feldspars show a close affinity to the bordering and cross-cutting pegmatite dikes. Thin feeding-stringers from the dikes to the large feldspar crystals and the continuity of many of the crystals with the dike material indicate their late development as crystalloblasts in the coarse Silver Plume-like matrix (Fig. 6).

In thin section the large phenocryst-like feldspars exhibit perthitic intergrowths and microcline twinning. In some the microcline grid is distinct over all of the grain. In others only small areas of microcline twinning occur, both around the edges and in the interior of the perthite, with fading contacts between the two. Boundaries of the large feldspars form very irregular contacts with both quartz and older, highly altered oligoclase. Small tongues of perthite amd microcline project into the bordering minerals (Fig. 10), and the fresh character of these two in contrast to the altered character of the bordering minerals is strongly suggestive of replacement. Smaller areas of fresh microcline occur abundantly along contacts and within "worm-eaten" remnants of the old plagioclase. Quartz is abundant in irregular aggregates forming areas commonly as large as the pink perthitic feldspar, i.e., up to an inch in diameter. The quartz replaces the old feldspar and is itself replaced by the perthite and microcline (Figs. 11 and 12). The quartz and microcline crystalloblasts are commonly contemporaneous, but a study of many con-

tacts between the two indicate the microcline to be later in the majority of cases. Myrmekite intergrowths are characteristic of both the coarse granitic rock and the gradational zones between it and the typical Silver Plume granite. The crystalloblastic development of the feldspars is not confined to the granitic rock, but occurs in many of the schistose bands and in large irregular areas of schist which appear partially absorbed or replaced by the granitic material around

FIG. 6.—Hell Gate migmatite showing porphyroblastic development of perthite and microcline in coarse granitoid matrix.

them (Fig. 4). These irregular areas of schist do not appear to be typical inclusions. In the majority of them the schistosity conforms to the trend of the regional schistosity and there does not seem to have been any splitting apart or distortion of the schistose laminae as might be expected if primary injection were the sole contributing cause of the rock mixing. So striking is the agreement of the structure of the isolated schistose areas with larger outcrops of schist in adjacent areas that drag folds, strike and dip of schistosity, and direction of overturning of axial planes of small isoclinal folds (all of which appear in the dark bands and shadows of the granitic rock)

may be measured to obtain trends of the regional structure. These structures, together with the evidence that the large feldspars developed later than the groundmass and are directly related to the late pegmatite dikes, suggest a replacement origin for the migmatite which has been called Hell Gate porphyry.[16]

In mapping such areas it is difficult to draw areal boundaries between massive or slightly schistose Silver Plume-like granite and areas of highly schistose rock, showing gradational boundaries into

FIG. 7.—Migmatite at head of Nolan Creek showing mixture of old schist and Silver Plume granite.

granite-like rock on one side, and into schist, which is of sedimentary origin, on the other. Areas of one are commonly surrounded by the other and this spotty distribution of massive granite and schist characterizes the migmatite zones throughout the range.

In the upper valleys and cirque basins of Nolan Creek and its tributaries, between Craig and Gold Dust peaks, glacial scouring has exposed several square miles of bare rock showing excellent examples of rock mixing on a large scale (Fig. 7). Areas of schist from a few hundred to a few thousand feet in length and half as wide show all degrees of migmitization, fading into zones of coarse-grained Silver Plume-like rock, which examined by themselves alone would be considered normal plutonic intrusions. For distances of one-half to

[16] Stark and Barnes, *op. cit.*, p. 474.

three-quarters of a mile the schistose zones can be traced across the cirque heads. The zones are not continuous but fade longitudinally along the strike, giving way repeatedly to areas of coarse granite. The schistose character disappears gradually as biotite becomes less important and quartz and feldspar increase proportionally. The increase of quartz and feldspar is first noticeable as small lenses and separate crystalloblasts in the schist, varying from a portion of an inch to an inch in diameter. The lenses grade into stringers which in turn widen into granitic zones with boundaries advancing irregularly both parallel to and across the schistosity.

Similar gradations between Silver Plume-like granite and schist occur on the east slopes of Mount Massive. Microscopic study of sections across such a zone, from pegmatite through a gradual transition into porphyroblastic schist, shows the following changes.

The pegmatite is composed largely of feldspar and quartz with only a small amount of biotite and associated grains of magnetite. Broadly twinned oligoclase, showing much saussuritization, is penetrated in many places by small tongues and embayments of quartz. The quartz shows similar replacive contacts with the biotite (Fig. 13). A few small areas of micropegmatite or myrmekite are present. Advancing toward the schist, the embayments in the saussuritized feldspar, filled by quartz, become more prominent. Vein-like stringers of quartz and microcline aggregates penetrate the schist along schistose planes. The old feldspars of the schist are reduced to felty masses of saussurite, and form web-like remnants (Fig. 14). Perthite and microcline increase in quantity and size of grain at the expense of the biotite, quartz, and saussurite. Myrmekite intergrowths occur around the borders of the perthite and microcline, and form scalloped areas in both the perthite and felty saussurite (Fig. 15). Massive schistose areas between the porphyroblastic schist zones show crystalloblastic texture with fresh microcline, perthite, and quartz (Fig. 16). Only scattered "worm-eaten" remnants of the old feldspars remain (Fig. 17). Biotite is fresh, apparently secondary after hornblende. In all cases it shows embayments filled by quartz.

The prominence of myrmekite and myrmekite-like intergrowths in all of the migmatized zones seems significant. The origin of myrmekite is a question on which there is much disagreement. Seder-

holm holds that in the strictest sense of the word it cannot be regarded as primary "since it has crystallized within the borders of another mineral, replacing its substance"—but as a deuteric form it may be regarded as a product of the plutonic activity which gave rise to the rock itself.[17] Gilluly, reviewing the literature on the origin of myrmekite and graphic textures, finds much evidence supporting replacement. He states, "it seems probable that the texture may be formed in any of at least four different ways: (1) by simultaneous intergrowths not in eutectic proportions, (2) by eutectic intergrowths, (3) by unmixing of solid solutions, and (4) by replacement." In the Sparta albite granite he believes a large part of the graphic textures are due to replacement.[18] Myrmekite in such rocks as the Hell Gate porphyry may be deuteric and not incompatible with a primary intrusive origin. But myrmekite in the massive and granitized schists, associated with increasing amounts of fresh quartz and with microcline replacing the quartz, gives evidence that it can also be due to plutonic contact action or regional metamorphism. This is in accord with Sederholm, Beche, and others.[19]

Even clearer evidence of the porphyroblastic nature of the Hell Gate porphyry may be seen south from Nast for several miles along Fryingpan River. Here large schist areas show gradational borders into the coarse granitic rock. Both formations are cut by numerous pegmatite dikes from which large pink feldspar crystals project into either the schist or granite host as the case may be. Similar feldspar porphyroblasts are scattered through the schist and granitic rock and commonly show connecting thread-like stringers of quartzose and feldspathic material to the pegmatite dikes (Fig. 8). Along the border zones the dark schist becomes increasingly lighter in color as more and more crystals of feldspar and quartz take the place of the biotite. In many places it is impossible to say where the schist stops and the granitic rock begins. In the field this change in the large areas of schist to granitic rock by the gradual increase of the large

[17] J. J. Sederholm, "On Synatectic Minerals," *Comm. Geol. Finlande, Bull. No. 48* (1916), pp. 138–39.

[18] Gilluly, *op. cit.*, 72–73.

[19] Sederholm, *op. cit.*, 137–39; Gilluly, *op. cit.*, 71–73.

feldspar and quartz crystals appears explainable only by porphyroblastic replacement.

Under the microscope the same phenomena are observed as described for other gradational zones. Fresh biotite forms at the expense of the altered pyribole of the schist. Quartz in stringers, lenses, and knots shows replacement contacts with the saussuritized feldspar (Fig. 20). Perthitic feldspar and microcline develop at the expense of both the quartz and saussurite (Fig. 19). Myrmekite forms along contacts of the old feldspar and microcline and quartz, within

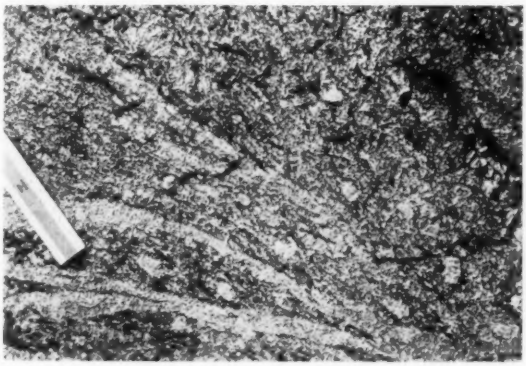


FIG. 8.—Migmatized schist showing pegmatite stringers feeding large plagioclase porphyroblasts in schistose matrix. Fryingpan Creek.

the body of the plagioclase, and in granulated zones between feldspars and other minerals (Figs. 18 and 19). Biotite and the felty schistose matrix of the schist become progressively less with the increase of quartz and feldspar.

In striking contrast to the gradational contacts there are irregular areas of schist, ranging from a few inches to many feet in width, which show extremely sharp contacts with the surrounding granitic rock. Some of the isolated schist areas are free from crystalloblasts; others show the development of quartz and feldspars along lines of schistosity similar to the crystalloblasts in the gradational schistose areas. Commonly a thin, dark band, usually less than an eighth of an inch, borders the schist areas. This is composed of a richer concen-

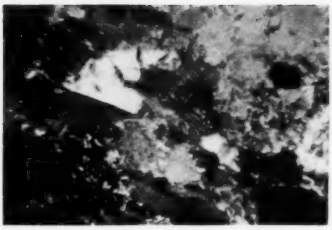


FIG. 9

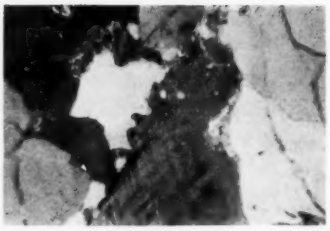


FIG. 10

FIG. 9.—Clear Creek schist showing development of myrmekite in matrix of chlorite and biotite. Crossed nicols, ×20.

FIG. 10.—Migmatite, Hell Gate. Perthite replacing quartz. Crossed nicols, ×20.

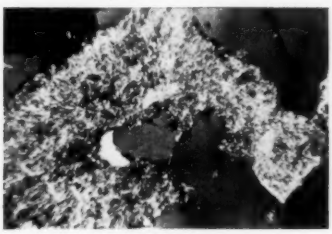


FIG. 11

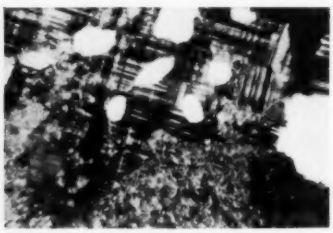


FIG. 12

FIG. 11.—Migmatite, Hell Gate. Saussuritized plagioclase replaced by quartz. Crossed nicols, ×60.

FIG. 12.—Migmatite, Lost Mans Lake. Microcline replacing quartz and saussuritized plagioclase. Crossed nicols, ×60.

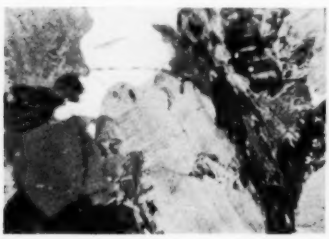


FIG. 13

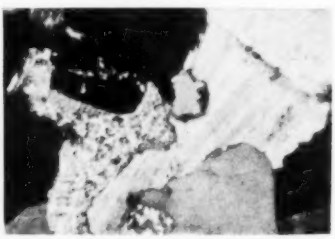


FIG. 14

FIG. 13.—Migmatite, Mount Massive. Quartz replacing biotite and being replaced by microcline. Crossed nicols, ×20.

FIG. 14.—Migmatite, Mount Massive. Quartz and saussuritized plagioclase replaced by perthite. Crossed nicols, ×20.

tration of biotite than occurs throughout the body of the schist. Similar biotite selvages occur along the contacts of some of the pegmatite dikes cutting the schists.

Biotite in the migmatized zones is commonly after amphibole and pyroxene. As relict bands and ghost lines it is one of the last of the dark minerals to disappear as the schists become progressively lighter with increasing amounts of quartz and feldspar. The biotite concentrations previously referred to, in contrast to the relict bands, appear to be due to reactions between the country rock and the invading solutions, favoring the formation of biotite along contracts. Clear evidence of this is seen in many of the large pegmatites where biotite forms in large flakes as a border mineral. In many places the selvages of biotite themselves become relicts as the schist inclusion and the wall rock on either side of the pegmatite become granitized. Wavy lines about schist areas suggest at first primary flow lines of viscous intrusion. On closer inspection, however, such lines are found completely surrounding many schist areas and in places successive concentric bands surround a core of schist. The center may be of massive schist, or schist containing porphyroblasts of quartz and feldspar, or schist that is completely altered into a granitic migmatite.

ORIGIN OF THE MIGMATITE ZONES

To what extent the mixed zones of schistose and granitic material exposed over such wide areas in the Sawatch Range are due to viscous intrusion, refusion, recrystallization, or replacement remains an open question. It has doubtless been evident, however, from the foregoing descriptions, that many of the outcrops are interpreted as showing evidence of actual transference of material and replacement of the original schists by feldspar and quartz from the invading batholiths. Such an interpretation is at variance with the ideas of Rosenbusch and the Heidelberg school of petrology and is in accord with the ideas of Sederholm, and others, who have studied zones of the mixed rocks.[20]

[20] Sederholm, "On Migmatites and Associated Pre-Cambrian Rocks of Southwestern Finland," *op. cit.*, pp. 1–21; Gilluly, "Replacement Origin of an Albite Granite near Sparta, Oregon," *op. cit.*, pp. 65–81. Both of these papers contain excellent bibliographies on migmatization.

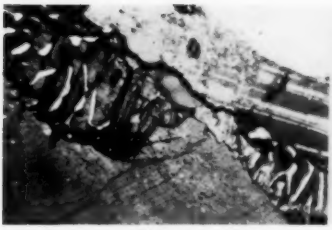


FIG. 15

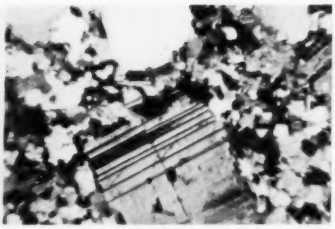


FIG. 16

FIG. 15.—Migmatite, Mount Massive. Myrmekite embayments in perthite and interstitial between plagioclases. Crossed nicols, ×60.

FIG. 16.—Migmatite, Mount Massive. Crystalloblastic texture in schist with porphyroblasts of quartz and plagioclase. Crossed nicols, ×20.

FIG. 17

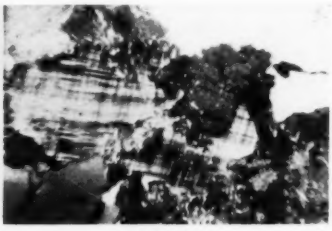


FIG. 18

FIG. 17.—Migmatite, Mount Massive. Remnants of schistose matrix replaced by microcline and quartz. Crossed nicols, ×20.

FIG. 18.—Migmatite, Fryingpan River. Myrmekite encroaching on quartz and microcline. Crossed nicols, ×20.

FIG. 19

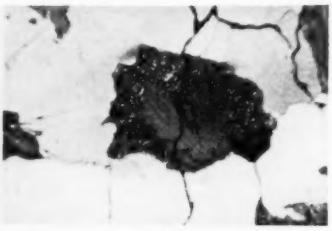


FIG. 20

FIG. 19.—Migmatite, Hell Gate. Microcline replacing saussuritized plagioclase, with myrmekite borders. Crossed nicols, ×60.

FIG. 20.—Migmatite, south of Nast. Remnant of saussuritized plagioclase replaced by quartz. Crossed nicols, ×20.

North and east of the Sawatch Range the valley of Tenmile Creek exposes a section of mixed rocks similar in character and probably continuous with the Sawatch schists. From field and laboratory studies of this area, R. S. Cannon, Jr., concludes that they were altered by processes of granitization on a large scale to migmatites.

> The granitization was accompanied by the introduction of quartz, microcline, and probably sodic plagioclase, which have replaced the original minerals of the rocks, and new minerals introduced by the agency of hot solution, similar to magmatic emanations, which were rich in silica and the alkalies.[21]

The problem is essentially one of field relations, for the primary textures of granitic invaded rocks are more or less obliterated. This is particularly true in the Sawatch Range where the migmatite zone is close to the roofs of the batholiths and where intrusions and recrystallizations have probably been repeated many times.

The microscope does offer much evidence for replacement in mineralogic and textural features, but it must be admitted that many of the features might be explained equally well by deuteric changes in slowly cooling igneous rock. Myrmekite, graphic intergrowths, cataclastic, and crystalloblastic textures are common phenomena in thin sections of the migmatites. Irregular contacts, corrosion edges, embayments, and projecting fingers of less-altered into much-altered minerals are suggestive of replacement, although any one of them might be formed in other ways. The abundance of these features, together with the increasing alkalic and sodic content of the late minerals, combined with field evidence of the crystalloblastic development of the large feldspars, the granitization of schists of varying composition by the apparent introduction of quartz and feldspar, the relict bands of biotite about the areas of schist in the granitic migmatites, and the preservation of regional structures in the schist bands with no evidence of any considerable distortions by viscous intrusion, all strongly suggest regional granitization on a large scale by replacement processes.

It is not thought that replacement occurred to the exclusion of other processes. Lit-par-lit intrusion is evident throughout the entire area and was undoubtedly concomitant with migmatization.

[21] R. S. Cannon, Jr., "Genesis of the Pre-Cambrian Rocks of Tenmile Valley, Colorado." Unpublished Master's thesis, Northwestern University (1933), p. 87.

But to assume that mechanical splitting of older schist by viscous intrusion can account for all of the granitic rock would mean that crumpling and compression have made room for many thousands of feet of new material and the intruded schists give no evidence of any such movement. To the contrary, many delicate structures, thin ghost stringers, the strike of schistosity, and small drags appear in the bands in the granitic rock. They show accordance with regional structures of large adjacent schist areas and apparently have been moved not at all, or only slightly in very few instances.

Not only do the lit-par-lit stringers, varying from extreme thinness to thicknesses of many feet, show pinch and swell outlines with no disturbance in the adjacent schists, but microscopically the boundaries are seen as irregular, sutured contacts of replacement. The nature of such intrusions is believed to be more replacive than displacive. Fenner suggests that invasion of magma in such intrusions may be preceded by the advance of a wave of metamorphism into the wall rock by which the character and composition of the original material are radically altered and that

> by deposition of magmatic minerals and the removal in solution of certain previous constituents, the composition tends to approach that of the magma itself—and when blocks of wall rock are finally engulfed in the magma their composition may be so changed that their assimilation effects but little change in the composition of the latter.[22]

Recrystallization and to a slight extent refusion or a combination of these processes have occurred locally and unquestionably played a part in the migmatization, but these processes alone do not give a satisfactory explanation of the wide areas of mixed schistose and granitic material. Schists of various types, quartzitic, biotitic, hornblendic, all become granitized into much the same sort of migmatite composed of alkalic feldspar (similar to that of the intruding granite) and quartz with less amount of biotite. The migmatization was accompanied in many places by intimate penetration of the granite ichor, and in the lower superheated zones fusion and to some extent actual viscous flow probably took place. But the recognition of a few widely scattered evidences of such phenomena is quite different from applying them to miles of granitized schists which show re-

[22] Clarence N. Fenner, "The Mode and Formation of Certain Gneisses in the Highlands of New Jersey," *Jour. Geol.*, Vol. XXII (1914), p. 701.

peated gradations into granitic rock and which contain numerous relicts of schistose structure, but no sign of appreciable movement by splitting apart of schistose laminae or crowding apart by viscous flow.

Unfortunately, chemical analyses are not available. To what extent they might shed light on the problem is not certain. We are dealing with migmatization at great depth and under high temperatures close to the batholithic roof. Schists in which true viscous intrusion is recognizable were probably recrystallized, granitized, and penetrated again and again by the magmatic emanations until they became composed largely of quartz, feldspar, and biotite, similar in many respects to the intruding granite. Thus analyses of the rocks now exposed would not give a comparison of the composition of the original schist and the migmatite, but simply a comparison of rocks which have undergone varying degrees of migmatization. In most of the outcrops at least two periods of mixing are evident—the first preceding the actual intrusion of the viscous magma as such, and the other following and initiated by the later intrusions of the batholith and accompanying pegmatite dikes.

In conclusion, the interpretation which seems least at variance with the field relations and which has the support of microscopic evidence suggestive of replacement is one of regional granitization or replacement involving the carrying out and the bringing in of large quantities of material by emanations, gaseous or liquid, from the invading batholiths. The sequence may have been somewhat as follows:

1. Intrusion at great depth of pre-Cambrian batholiths into areas of highly folded schists of varying composition.

2. Heating of the schists to high temperatures far in advance of the actual intrusion of the magma and over a long period of time.

3. Penetration of the superheated schists by gaseous or thinly fluid emanations from the consolidating batholiths with replacement and recrystallization forming granitized or migmatized zones above the batholiths.

4. Intrusion of the granitized and migmatized schists by viscous magmas in the form of stock-like masses and lit-par-lit stringers, sills and dikes of pegmatite.

5. Late period of pegmatite intrusions accompanied by porphyroblastic development of large pink feldspars in superheated schist, in the mixed zone of schist and granite, and in the earlier intrusions of the granite.

6. As these processes continued it is assumed that large masses of schist were replaced leaving in many places only small areas of biotite to give relict structures to the newly formed granitic rock and that only locally was the fusion sufficient to cause actual movement in the ordinary sense of flowage in the migmatized zones.

ACKNOWLEDGMENTS.—Replacement as a prominent factor in the origin of the Sawatch schists was first suggested to the writer by Dr. B. S. Butler and to him and other members of the U.S. Geological Survey working in Colorado acknowledgments are gratefully made. To Dr. T. S. Lovering, who has given generously of his time in the field and who has been a penetrating critic of the replacement interpretation, the writer is greatly indebted. To Drs. C. H. Behre, Jr., W. E. Powers, and A. L. Howland of Northwestern University special thanks are due for aid in the field and critical reading of the manuscript. F. F. Barnes, R. S. Cannon, Jr., and E. S. Osborn gave valuable aid as field assistants during different field seasons.

GEOLOGY OF THE NORTHEASTERN PART OF THE IDAHO BATHOLITH AND ADJACENT REGION IN MONTANA[1]

CLAUDE M. LANGTON
University of Chicago

ABSTRACT

The region is composed mainly of sediments of the Belt series and of gneisses and schists in the immediate vicinity of the Idaho batholith. The structures become more complex as one approaches the batholith, and evidence is given for two periods of folding and faulting of which the later deformation occurred near the time of the batholithic emplacement. Important is the fact that a series of thrust faults parallels the northeastern portion of the batholith; it is believed that these thrusts have been produced by batholithic forces pushing outward. Assimilation seems to have been of little importance in the emplacement of the batholith, but stoping has played an important part.

The Bitterroot Valley, previously considered due to normal faulting, is found to have experienced a complex history consisting of thrust faulting, intrusions, underthrusting, and later normal faulting.

INTRODUCTION

The area described in this paper lies within Missoula, Ravalli, and Granite counties, Montana. It extends southward from the city of Missoula nearly to Hamilton, and from the Idaho-Montana boundary eastward to Rock Creek, covering, in all, about 1,300 square miles. The area is bisected by the Bitterroot River into eastern and western divisions, the former comprising the Sapphire Range; the latter, the Bitterroot and Graves Creek ranges (Fig. 1).

Work was commenced in the summer of 1932 in the northern part of the area where the rocks show the least complexity. After the simpler structural patterns had been interpreted, the work progressed southward into the more complexly deformed area which is nearer the northeastern margin of the Idaho batholith. In all, the writer spent 130 days of actual field work, mapping the structures. Previous to this, Dr. C. H. Clapp of the University of Montana, had mapped the area in a reconnaissance manner, but his maps have not been published, although they have been freely consulted by the writer.

[1] Published with permission of the Montana State Bureau of Mines and Geology.

Much credit is given to Dr. Clapp, for use of his maps; and since he was in charge of the field work and was with the writer during nearly one-third of the time spent in the field, many interpretations

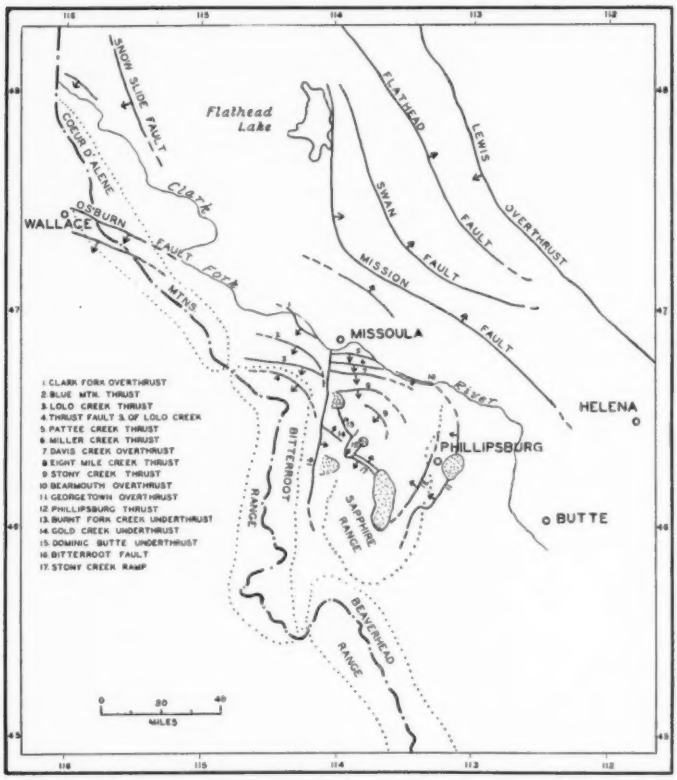


FIG. 1.—Index map, showing major fault patterns of Western Montana

of the structures in the complex areas are primarily his own. Dr. R. T. Chamberlin offered many valuable suggestions during the preparation of the manuscript, and to him the writer is deeply indebted. Also to Professor A. Johannsen thanks are given for his aid in the examination of the rock sections.

PHYSIOGRAPHY

The physiography of the Bitterroot Range has been well described by Dr. W. Lindgren.[2] Only the characteristics germane to the structural problems of the region are given here, of which the major feature is the uniform dip of the eastern front of the range to the Bitterroot Valley. This bold front is a persistent and regular one, and it has an average dip of about 25°. It extends the full length of the Bitterroot Range and comprises a zone composed of both sedimentary and granite gneisses, which will be described in detail later. Another feature of the Bitterroot Range is the gradual increase in altitude of the summit peaks from north to south, showing a greater elevation of the southern part of the region. The ruggedness of the Bitterroot Range, because of intense glaciation on the underlying rocks of gneisses and schists, is probably not exceeded by any other ranges within the Rocky Mountains (Fig. 2).

The physiographic development of the Sapphire and Graves Creek ranges is in strong contrast to that of the Bitterroot Range; but, like the Bitterroot Range, the Sapphire Mountains have been uplifted considerably higher in their south extension than in the north. In general the range resembles a broad, dissected plateau. The major streams within the Sapphire Range mostly head southward and are in part subsequent and in part superimposed.

The Bitterroot River is the major stream within the area. Because of its significant relation to the geologic structures of the region, it is described most fully in this paper. The valley proper is about 65 miles long and nearly 9 miles in width, with a nearly straight north-south trend. On the west, the Bitterroot Range rises with its remarkably even slope and deeply incised canyons; on the east, with gentler slope and far less pronounced outlines, are the foothills of the Sapphire Range. Roughly outlined, the shape of the valley is that of a broad-bottomed, unsymmetrical boat, narrowing at both ends. Few, if any, outcrops occur directly within the valley except from the mouth of Lolo Creek northward. Within this short distance, the valley loses its basin-like shape and the river is superimposed upon faulted rocks of the Belt series. The depth of the river

[2] W. Lindgren, "A Geological Reconnaissance across the Bitterroot Range and Clearwater Mountains in Montana and Idaho," *U.S. Geol. Surv. Prof. Paper 27* (1904).

FIG. 2.—Photograph taken looking south up the South Fork of Lolo Creek, Bitterroot Range. Heavenly Twins in the central background; elevation, 9,329 feet.

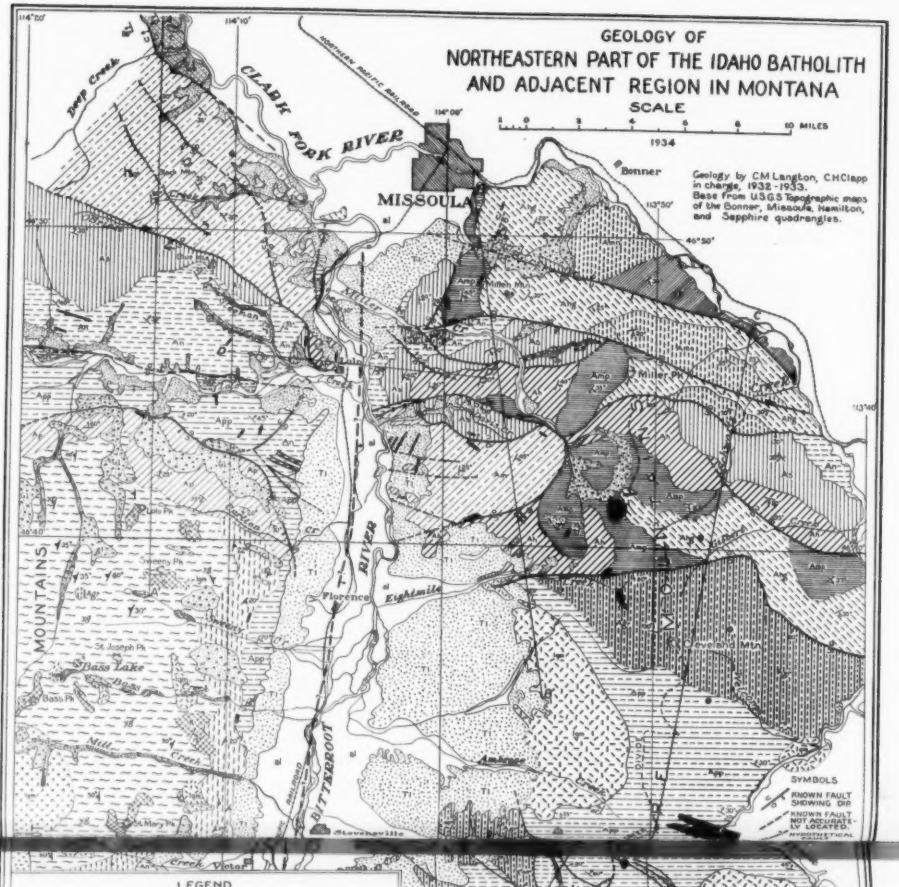
gravels, or lake deposits, as shown by a well drilled near Corvallis, is over 1,100 feet; and the total depth of the basin may be twice this amount. The valley is probably a downwarp with the western side a complexly sheared fault zone. Perhaps with the filling of the basin in Tertiary time, with greater uplift in the southern part of the basin, and damming of the Snake River with lava flows, a spillway was developed on the north where now exists the mouth of the stream, and hence the reason for the narrowing of the river valley near the town of Lolo and northward.

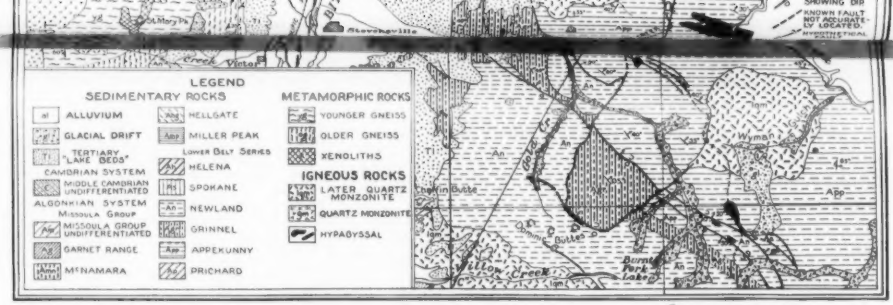
STRATIGRAPHY

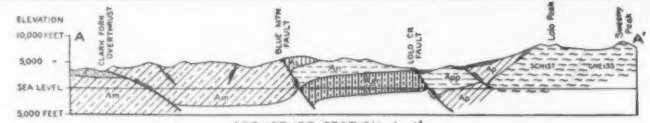
The predominant sedimentary rocks of the area belong to the Belt series. Probably nowhere else in Montana are so many of the Belt formations represented in an area of equal size as in the northern part of the Sapphire Range. The sediments of this area may represent the maximum thickness of the Belt series and probably reach well over 50,000 feet.[3] The formations vary from 2,000 to 8,000 feet in thickness and are largely composed of argillites, sandstones, and quartzites. Each formation usually contains some beds lithologically similar to beds in other formations of the same series so that it is often necessary to ascertain the relations of the formation being mapped to the formations above or below before its place in the stratigraphic column can be definitely fixed. The age of the formations becomes progressively older from the Clark Fork River southward, the reasons for this being threefold: (1) thrust faulting from the south, (2) synclinal nature of a narrow lineament to be discussed later, and (3) a relatively greater uplift of the southern part of the range than of the northern part. However, a repetition of younger formations occurs in the extreme southern portion of the area mapped. This is due to underthrust faulting. Because of the structural complexity of the area, no attempts were made by the writer to measure the sections. However, the type sections[4] of the Hellgate and Miller Peak formations occur in the extreme northern part of the Sapphire Range.

[3] C. H. Clapp, "Geology of a Portion of the Rocky Mountains of Northwestern Montana," *Mont. Bur. of Mines and Geol., Mem. 4* (1932), p. 18.

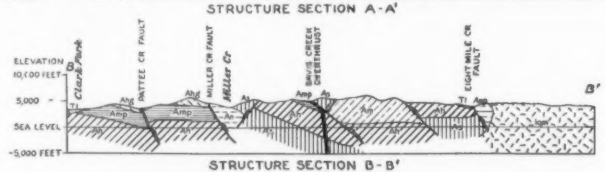
[4] C. H. Clapp and C. F. Deiss, "Correlation of the Algonkian Formations in Montana," *Geol. Soc. Amer. Bull. 42* (1931), pp. 673–96.


GEOLOGY OF
NORTHEASTERN PART OF THE IDAHO BATHOLITH
AND ADJACENT REGION IN MONTANA
SCALE
1934
Geology by C.M. Langton, C.H. Clapp in charge, 1932-1933.
Base from U.S.G.S. Topographic maps of the Bonner, Missoula, Hamilton, and Sapphire quadrangles.
CLARK FORK RIVER
MISSOULA
Bonner
Miller Pk.
Florence
Eight Mile
Bass Lake
Mill Creek
St. Mary Pk.
BITTERROOT MOUNTAINS
BITTERROOT RIVER
SYMBOLS
KNOWN FAULT SHOWING DIP
KNOWN FAULT NOT ACCURATELY LOCATED.
HYPOTHETICAL
LEGEND

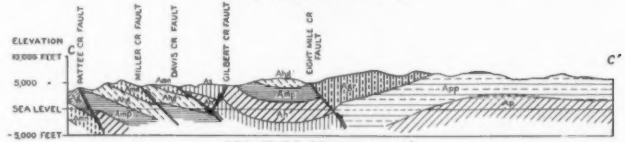




STRUCTURE SECTION A-A'



STRUCTURE SECTION B-B'



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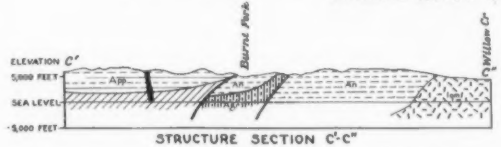
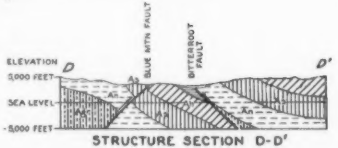


STRUCTURE SECTION C'-C"



STRUCTURE SECTION D-D'

FIG. 3

Since Emmons and Calkins[5] have described in detail the Lower Belt series in the Philipsburg area, which lies on the east adjacent to the Sapphire Range, and Clapp and Deiss[6] have recently described the "Missoula group" or Upper Belt series, only a tabular description is given here (Table I).

A few square miles of Paleozoic limestone lie along the Clark Fork River in the extreme northwest portion of the area. A definite age cannot be assigned to the limestone, as no fossils were found. It is here tentatively correlated with the Hasmark formation of Cambrian age, since, lithologically, it compares well with that formation described by Calkins in the Philipsburg district. However, a very petroliferous odor is characteristic of the limestone, which is not true of the Hasmark formation but is more typical of the Jefferson limestone of Devonian age. On the other hand, the Jefferson limestone, in contrast to these limestones, carries an abundant fauna. In view of the fact that the contact of the Upper Belt rocks with the limestone is a faulted one, we must await the finding of fossils before any permanent correlation is made.

No other sediments except slightly consolidated Tertiary lake beds, late Pleistocene deposits, and Recent gravels occur within the area. These are confined to the major stream valleys and were not studied in detail; they are, therefore, not differentiated on the map. In fact, no exposures carrying fossils of definitely Tertiary age were noted, but the indurated gravels covering the lake benches on either side of the Bitterroot Valley are retained on the map as Tertiary. Undoubtedly these deposits of gravels and subangular boulders represent, in part, Pleistocene fill in "Lake Missoula."[7] These benches or terraces are readily observed along the major streams up to 4,300 feet in elevation, which represents the height which Lake Missoula once attained. The lower benches, however, probably consist of Tertiary lake beds now covered by the later gravels, as Lindgren[8] has described a deposit of lignite coal of Tertiary age near the

[5] W. H. Emmons and F. C. Calkins, "Geology and Ore Deposits of the Philipsburg Quandrangle, Montana," *U.S. Geol. Surv. Prof. Paper 78* (1913).

[6] Clapp and Deiss, *op. cit.*, pp. 673–96.

[7] J. T. Pardee, "The Glacial Lake Missoula," *Jour. Geol.*, Vol. XVIII (1910), pp. 376–86.

[8] Lindgren, *op. cit.*, pp. 111–13.

TABLE I

SEDIMENTARY ROCKS

Geologic Age			Formation	Thickness	Character
CENOZOIC	Quaternary	Recent	Alluvium		Silt, sand, and gravel that form flats along the streams are locally gold-bearing.
		Pleistocene	Terrace gravels Lake Missoula beds Glacial drift		Moderately thick deposits covering Lake Missoula terraces or benchlands along Clark Fork and Bitterroot valleys extending up to an elevation of 4,300 feet. Few exposures of varved clays along Clark Fork River. Glacial drift but slightly weathered; probably re-worked lateral and terminal moraines.
	Tertiary	Oligocene-Miocene and Pliocene	Lake beds		Massive silts underlying bench gravels on east side of Bitterroot Valley. Generally concealed by superficial material, and seen only in road cuts. In southern end of the Bitterroot Valley some coal seams outcrop. In most valleys of western Montana, volcanic ash is common.
PALEOZOIC	Cambrian		Hasmark? formation	1,000± ft.	Dolomitic, massive-bedded, grayish weathering limestone, with a characteristic petroliferous odor, lying disconformably upon whiter, siliceous limestone, interbedded with brownish cherty laminae with some shale. Unfossiliferous. May represent the upper part of the Silver Hill, Hasmark, and lower part of the Red Lion formations.
Faulted Contact					
ALGONKIAN	Missoula Group*		Garnet range formation	6,500± ft.	Upper 3,000 feet consist of brownish and greenish micaceous, thin-bedded argillitic quartzite overlying 300 feet of pure coarse-grained purple quartzite. Beneath this purple quartzite are 1,600 feet of brown, green, and gray quartzitic sandstone, overlain by another 1,600 feet of brown, green, and gray micaceous quartzites and argillites. Only the upper part is exposed in the mapped area.

* Descriptions of Missoula Group taken from Clapp and Deiss; Lower Belt descriptions, from Calkins, Philipsburg area.

TABLE I—*Continued*

Geologic Age		Formation	Thickness	Character
ALGONKIAN—*Continued*	Missoula Group—*Continued*	McNamara	3,000± ft.	Upper 1,800 feet consist mostly of alternating beds of red, gray, and greenish, fine-grained, mud-cracked argillites and sandstones. Lower part comprises pink and white massive quartzite interbedded with maroon-colored sandy argillites.
		Hellgate	2,200± ft.	Massive red to pinkish gray quartzite. Cross bedded, ripple marked, and interbedded with thin beds of red argillite.
		Miller Peak	2,900± ft.	Massive to thin-bedded, purple and gray sandstones and argillites. Lower part comprises calcareous buff weathering thin-bedded mud-cracked argillites.
	Lower Belt	Helena	4,000± ft.	Thin-bedded, argillaceous and sideritic limestone with parts dolomitic. Beds weather to a buff or cream color and often show "molar tooth" structure.
		Spokane		Upper part massive to thin-bedded lavender-colored quartzites. Lower 2,000 ft. consist of greenish-gray and in part calcareous argillites showing ripple marks.
		Newland	4,000± ft.	Impure argillitic, dolomitic, and sideritic limestones, with some blue, thin-bedded, ripple-marked argillites.
		Grinnell	7,000± ft.	Upper portion consists of bluish-gray, fine-grained thin-bedded argillites grading downward into more massive-bedded gray quartzitic argillites, commonly ripple-marked and with layers of reddish gray quartzites.
		Appekunny	6,000+ ft.	Predominantly massive, bluish-gray and light gray argillitic quartzites, grading downward into very massive gray quartzites.
		Prichard	5,000± ft.	Predominantly brownish sandstones often containing feldspar, highly metamorphosed to biotite-muscovite schist in the area mapped. The formation is intruded by the older gneiss on Lolo Mountain.

south end of the valley on the Nez Perce Fork; also along the other major valleys of western Montana remains of both Tertiary vertebrates and invertebrates are widely known.

IGNEOUS ROCKS

GENERAL

The igneous rocks within the area are numerous; and the region is literally spotted with small bosses, dikes, and sills. They are similar in composition, and their mineral components show a close relationship between the hypabyssals and the plutonites, although only about thirty-five different specimens have been studied by the writer. A few of the different types are briefly described here. In general the majority of the hypabyssal rocks are slightly soda rich, as shown by blue hornblende (riebeckite) or albite or oligoclase feldspar.

IDAHO BATHOLITH

The Idaho batholith, which is exposed over an area of approximately 16,000 square miles,[9] is one of the greater batholiths of North America. But what is thought to represent the true massive phase of the batholith comprises an area of only a few square miles in the extreme southwestern corner of the region. Practically the entire area of nearly 200 square miles mapped in the Bitterroot Range is composed of schists, gneisses, and later unaltered injections which are related to the batholith. Megascopically the massive phase is a normal granular rock, made often roughly porphyritic by the development of large orthoclase and oligoclase crystals up to an inch or more in diameter. The color is prevailingly a light gray, but the slightly weathered outcrops assume a yellowish-gray color. Biotite is always present, and muscovite is common. Quartz is often abundant in medium-sized grains, but the amount varies considerably; while the feldspars are represented by both orthoclase[10] and oligoclase, the

[9] C. P. Ross, "Mesozoic and Tertiary Granitic Rocks in Idaho," *Jour. Geol.*, Vol. XXXVI (1928), p. 676.

[10] A. L. Anderson and A. C. Rossor, "Composition of Part of the Idaho Batholith, Boise Co., Idaho," *Amer. Jour. Sci.*, 5th ser., Vol. XXVII (1934), pp. 287–94. Described the core of the batholith as composed of microcline instead of orthoclase. No microcline has been observed in the sections studied by the writer, and the percentage of orthoclase is somewhat less than the amount of microcline as calculated by them.

latter in large quantity. Under the microscope perthite is frequently seen; and in some cases the oligoclase is complexly twinned, giving nearly a microcline plaid effect. The rock contains far too much oligoclase to be classed as a normal granite but varies from a quartz-monzonite (adamellite) or grano-diorite to a true tonalite. Few accessory minerals except zircon and apatite were noted, though titanite occurs abundantly in the hornblende-rich segregations of the same granite. All the specimens studied show some effects of pressure, as indicated by the undulating extinction of the quartz. The typical specimen contains the following essentials: biotite, 10 per cent; quartz, 33 per cent; oligoclase, 41 per cent; and orthoclase, 16 per cent.

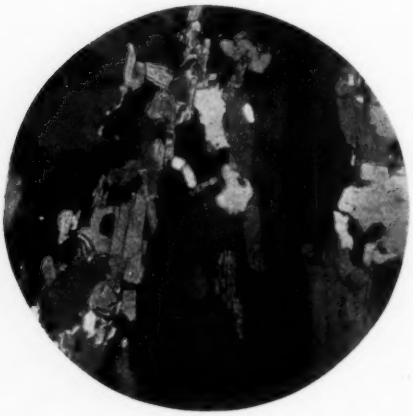


FIG. 4.—"Younger gneiss." Cross Nicols × 38

Younger gneiss.—Surrounding the more massive granite described above, is a border phase of schlieren gneiss, which in turn is bordered on the east by what is believed to be a much older gneiss. The younger gneiss grades outward with increasing schistosity from the massive granite. The zone of schlieren gneiss extends for a distance of over 12 miles northward from the northeast margin of the batholith and forms the major part of the Bitterroot Range from St. Joseph Peak northward beyond Lolo Peak. On the east side of the batholith this gneiss continues southward with an average width of nearly 5 miles, but narrows rapidly southward until, between Sweathouse and Bear Creek, it is less than a mile in width. This zone is highly intruded by numerous leucocratic stocks and tonalite-aplite dikes, as well as pegmatites and hornblende-rich dikes. Some of these intrusions are sheared and foliated. The outer part of the zone con-

tains numerous xenoliths and remnants of roof pendants, the latter being most commonly found on the higher ridges. The strike of the gneiss generally parallels the border of the massive granite, but the dip varies considerably, giving an asymmetrical anticlinal-like structure. The west limb is the steeper (50°–80°), while the eastern flank dips toward the valley at a lower angle. The anticlinal structure trends slightly west of north, and near its axis the schlieren gneiss is less prominently developed and is nearly horizontal. The massive phase of the batholith lies to the west of the structure, and the western limb apparently dips beneath it. The cause of this structure may be a large intrusion which is not exposed at the surface. On the extreme north, the gneiss is more schistose than on the east. In places the gneiss is decidedly crinkled perpendicular to the normal cleavage planes, and biotite and muscovite make up a large portion of the rock. It is not impossible that this crinkled gneiss may be older and may belong either to the outer zone of gneiss described below or may have been derived in part from the sandy argillitic Prichard formation.

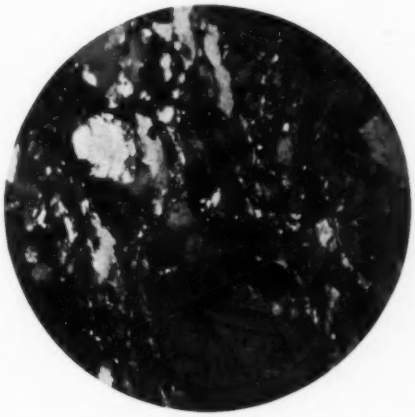


FIG. 5.—"Older gneiss." Granulated Cross Nicols × 36.

Thin sections of the schlieren gneiss show little orthoclase but a high percentage of muscovite. The rock is, however, the metamorphosed equivalent of the massive granite. An average of five specimens gives 9 per cent biotite, 17 per cent muscovite, 23 per cent oligoclase, 47 per cent quartz, and only 3 per cent orthoclase. Of the few accessory minerals garnet appears to be in larger amounts than in the massive granite.

Older gneiss.—A gneissic zone, which is thought to be older than

the schlieren gneiss just described, extends along the eastern front from Carlton Creek southward for over 50 miles. This zone averages less than 2 miles in width from Carlton Creek to Sweathouse Creek but widens to over 3 miles along Bear Creek. The gneiss dips toward the valley at an angle of 15°–30°, which is nearly parallel with the slope of the mountain front. This older gneiss may also curve westward in the northern part of the range; but, because of the strong schistosity, it could not be differentiated there from the younger gneiss. The contact of the two zones is fairly sharp and readily detected in some places, but in others there may be a gradational zone. The writer cannot do better than quote Lindgren's[11] description of this gneiss.

> The nomal gneiss from Mill Creek,[12] two miles above the mouth of the canyon is a plainly schistose rock with large orthoclase crystals pressed into partly lenticular shape. Biotite and a little muscovite lie in flat aggregates between streaks of pressed feldspar and quartz. There is much cataclastic action and formation of new allotrimorphic aggregates along wavy lines, which indicate schistosity. Large feldspar and quartz grains, when crossed by these lines, are greatly crushed. On the whole, however, the rock has similarity to the normal Bitterroot granite.
>
> Stronger crushing action near the mouth of the canyons simply results in emphasizing the characteristics already referred to. The sinuous lines along which most active recrystallizing movement is in progress multiply, and at last the whole rock is transformed into a fine-grained aggregate traversed by wavy streaks of finely distributed biotite and a little muscovite, and in this mass lie as pseudophenocrysts the irregular, more frequently lenticular remains of larger grains. These are often cut by parallel cracks which dip about 70° east, and which are sometimes opened and filled by secondary quartz, suggesting a stretching movement.

Because of these numerous slipping planes paralleling the essentially regular slope of the east front of the range, Lindgren postulated the Bitterroot fault, which will be discussed later.

Thin sections of this gneiss have been studied, but the writer fails to agree with Lindgren that the rock is but the metamorphosed equivalent of the younger gneiss or the massive granite. It seems

[11] Lindgren, *op. cit.*, p. 37.

[12] The Mill Creek referred to by Lindgren is not the Mill Creek shown on this map, but occurs farther south and is also a western tributary of the Bitterroot.

more likely that this gneiss is the equivalent of an older true granite and not the quartz monzonite or granodiorite from which the schlieren gneiss developed. The average percentages of the essential minerals are as follows: orthoclase, 45 per cent; quartz, 34 per cent; muscovite, 3 per cent; biotite, 5 per cent; and oligoclase only 13 per cent. It is noteworthy that there is but slight development of muscovite and biotite, and that orthoclase is three times as abundant as oligoclase. It seems certain that the relative amounts of the potash feldspar and oligoclase of the two gneisses indicate a difference in origin. The former, or younger, gneiss has been developed from the true quartz-monzonite or granodiorite; whereas the latter is probably older and derived from a true granite which may be much older.

Xenoliths.—Only a few of the larger xenoliths are shown on the map, and their boundaries are tentatively drawn. They consist of quartzites, sandstones, greenish metamorphosed limestones, and a few blocks of the older gneiss. The xenoliths are most numerous near the margin of the younger gneiss, show little or no rounding, and are nearly always ptygmatically folded with the lit-par-lit injections which probably make up 50 per cent of the blocks. Some of the xenoliths conform in strike and dip with the gneiss, but more commonly they are irregularly arranged.

Roof pendants.—Roof pendants consisting of quartzites and brownish sandstones occur on the crests of the higher ridges and in the mountain peaks. Their presence is easily detected at some distance by the reddish brown weathering of the sandstones. Like the xenoliths, the pendants show close folding with lit-par-lit injections which locally form a large part of the rock. These injections vary considerably in thickness within short distances and form lenses or even nearly spherical bodies (Fig. 6). In some places the bedding or planes of schistosity bend around the injected masses; whereas in other places the injections transect the cleavage planes. Lindgren[13] found no sediments remaining with the feldspar and mica schist in the mechanically weathered material on the ridges; and therefore suggested that these upper ridges, as on St. Mary's Peak, represent

[13] Lindgren, *op. cit.*, p. 37.

remnants of an older schist probably Archean in age. More detailed work, however, shows that not only does some sandstone occur on the tops of the ridges but also that sandstone xenoliths occur below these pendants, and the possibility of an Archean age of the gneiss is eliminated.

A most interesting roof pendant about 2 miles in length occurs on the spur north of the mouth of Mill Creek. It is composed of three limestone beds which are repeatedly faulted against bluish

FIG. 6.—Spherical "eyes" of granite in a roof pendant on ridge north of Carlton Creek.

quartzitic argillites. These beds undoubtedly represent the Grinnell or Appekunny and Newland formations. The strike of the bedding and of the faults nearly parallels the Bitterroot Valley. Both the limestone and quartzitic argillites also show slickensides with a dip similar to that of the gneiss. The pendant extends across the contact of both the older and younger gneiss, indicating that the former, as well as the latter, is post-Beltian in age.

Assimilation.—Evidence of assimilation in either the xenoliths or border sediments is meager. The xenoliths are exceedingly angular; and even small inclusions of quartzite, highly recrystallized, show no evidences of solution. In connection with lit-par-lit injections into schists or gneisses, assimilation is a recognized phase of the process of granitization. But within the lit-par-lit zones of both

the roof pendants and within the older gneiss, there is no apparent hybridism. Sillimanite was, however, found to the extent of 5 per cent in one specimen near the contact of a xenolith. On the whole, assimilation appears to have played a small part.

Stoping.—Stoping apparently has played a more important rôle in the emplacement of the batholith than has assimilation. The northern part of the range, from Carlton Lakes throughout the area mapped as Prichard, is truly a shatter zone composed of Prichard sedimentary rocks riven with many apophyses forming a network of dikes. Many of these blocks have been completely surrounded by magma and have settled within it to at least 2,000 feet below the roof, so as to be now exposed in the bottoms of the cirques as well as along the deeply incised gulches in Carlton, Sweeney, and other creeks. Nevertheless, the angularity of the blocks is as apparent in these xenoliths as in the blocks which appear to have floated on top of the magma. Although the northern contact of the intrusive gneiss with the sediments appears on the map to be fairly smooth, detailed mapping would show it to be more irregular.

STOCKS

The Willow Creek stock intrudes the Newland limestone near the southern boundary of the area east of Corvallis. Only the northern margin of the stock was traced, but it probably has an exposed area of over 15 square miles and is elongated in an east-west direction. Three specimens examined show that the rock varies considerably in the quartz-feldspar ratio but belongs to the leuco-quartz monzonite family. The rock averages about 35 per cent quartz, 30 per cent orthoclase, 32 per cent oligoclase, with less than 5 per cent biotite. Muscovite, apatite, and zircon are sparingly persistent.

The Boulder Basin stock comprises an area of over 17 square miles between Rock Creek and the crest of the Sapphire Range. Its outline is nearly square. In places the granite is somewhat sheared; but the Dominic Butte underthrust could not be traced in it, suggesting that the granite is perhaps younger than the underthrust. It is similar in composition to the Willow Creek stock.

The Ambrose Creek stock, which also is similar in composition to the other two, has an exposed area of about 25 square miles; but

the general trend of the exposed contact would indicate that over half of the stock is covered by gravels. The eastern margin of the mass is interesting because of its very regular contact with the Appekunny quartzites. Time was not available, nor exposures of the rocks adequate, to apply Cloos's methods on the flow structure. Some evidence of shoving, however, is manifested by (1) definite underthrusting of the Appekunny quartzites on the ridge near the northeast contact, and indirectly perhaps by (2) absence of doming of the country rock, as is conclusively shown by the dip of the sediments beneath the stock on the south and east, and (3) lack of evidence for stoping, such as xenoliths, blocky contacts, and lit-par-lit injections.

HYPABYSSALS

The dikes, sill-like injections, and small bosses within the area are very numerous. Few of these smaller injections can be traced for any great distance, but their relations to the later deformation of the region are clear. The dikes, which vary in type from monzo-gabbros through tonalites and quartz monzonites, usually follow the strike of the faults. In fact, they are so numerous along the faults that one always looks for faulting if a dike is found, or looks for a dike to give further evidence of a supposed fault. Most of the dikes are usually somewhat sheared and hydrothermally altered, but some are fresh and appear to be slightly later than the faulting. Evidence that faulting and injection went on simultaneously was seen near the northern contact of the Boulder Basin stock. Here an injection was noted intruding along a fault in quartzite with a later fault offsetting the earlier one and the dike.

A small area of andesite occurs along the Clark Fork River north of Schwartz Creek. No flow structure was noted, and the contact is obscured by drift. The Andesite may be a dike intruding along the Pattee Creek fault or it may be a remnant of a flow, as Pardee[14] has reported dacite extrusives a few miles to the east.

AGE OF THE IDAHO BATHOLITH

Ross[15] has summarized the literature concerning the intrusive bodies in Idaho and southwestern Montana but has left the age of

[14] Pardee, *op. cit.*, p. 169 (also map).

[15] Ross, *op. cit.*, pp. 673–93.

the Idaho batholith still an open question. Little information on the age of the major batholith can be obtained from the area studied. That the major batholith is composite, comprising a group of batholiths and smaller bodies differing somewhat in age, is evident. It is very likely that the northern third or more of the Bitterroot Range consists of intrusions that are later than the schlieren gneiss, which is thought to be of the same age as the Idaho batholith. If we assume that the minor structures of this area, to be discussed later, are closely related to the batholith, it follows that the batholith is not only Cretaceous or Eocene in age but that its emplacement followed the major or north-south trending structures which developed in the earlier part of the Laramide deformation. On the other hand, it is not at all impossible that the batholith may in part be Jurassic, as some have supposed, and that only the eastern or northeastern portions are of later age. This would be in harmony with Lindgren's[16] suggestion of a progressive eastward migration of the later intrusions.

STRUCTURE

GENERAL

In western Montana the Rocky Mountains have been divided on a structural basis into a northern area of linear ranges trending in a general N. 30° W. direction and a southern area in which the mountain ranges are diversely arranged.[17] The northern linear ranges

> are in strong contrast to that of the southern ranges of the state, because their structure is simpler, and because they are composed almost entirely of sedimentary rocks; although igneous rocks do form conspicuous sills and in a few places small granitic stocks. To the south, however, igneous rocks, in batholithic, injected, and volcanic masses become the dominant rocks of many of the mountain clusters and diversely arranged linear ranges.
>
> The zone separating the two geologic divisions of western Montana is narrow and fairly well defined. It extends slightly southeast from the Cœur d'Alene district of northern Idaho to Missoula and thence almost due east to Helena.[18]

[16] W. Lindgren, "The Igneous Geology of the Cordilleras and Its Problems," *Problems of American Geology* (1915), pp. 261–62.

[17] R. T. Chamberlin, "The Building of the Colorado Rockies," *Jour. Geol.*, Vol. XXVII (1919), p. 148.

[18] Clapp, *op. cit.*, p. 17.

This separating zone, or lineament, is in general synclinal; and from the Cœur d'Alene district eastward to Rock Creek it is an area of Belt sediments. East of Rock Creek, the rocks within this synclinal zone consist mostly of Paleozoic and Mesozoic sediments which are closely folded, broken by thrust faults, and intruded by small stocks.

The area which we are considering lies just south of, and partly within, this structural lineament; and in general its structures are more closely related to the complexly faulted and diversely arranged mountains than to the simple linear ranges of northwestern Montana. The Bitterroot Range, however, differs from the other ranges south of this lineament in having a linear, north-south trend, in being narrow in proportion to its length, and in standing boldly above the summits of the ranges to the east, north, and west.

The most striking structural features of the region are a series of nearly parallel thrust faults which trend in an east-southeast direction and which cut across older structures having a north-south trend (Fig. 3). Evidence for two episodes of folding and faulting is strong. The older north-south trending structures were probably produced during the earlier part of the Laramide deformation, or contemporaneous with the upthrust faulting and folding which produced the major linear structures north of the lineament.[19] The later deformation produced the east-southeast trending structures of this region, particularly overthrust and underthrust faults.

FOLDING

In recognition of the two distinct episodes of deformation the folds of the region may be classified as those of the earlier group and those of the later group, corresponding with the earlier and later deformations.

Earlier folds.—The folds of the earlier deformation are large, simple in structure, and have a general north-south trend as a result of easterly directed stresses. Examples of these structures may be seen in both the Sapphire and Graves Creek ranges. Between the series of faults noted above and extending from the Clark Fork River to Cleveland Mountain in the Sapphire Range, a synclinal structure, traversed from east to west by the thrust faults, is readily observed.

[19] *Ibid.*, p. 29.

The synclinal axis trends slightly east of north and plunges southward. Each successive fault to the south brings up older formations within the syncline and offsets these formations to the eastward, particularly on the western limb of the syncline. This offsetting is very noticeable when tracing the Hellgate formation from University Mountain, east of Missoula, across the Pattee Creek fault to Mitten Mountain, and southward across the Miller Creek fault to Miller Peak. Farther south the Hellgate quartzite again appears on Gilbert Creek, but the general plan of the structure is altered by the northward dipping Gilbert Creek wedge fault. South of the Eight Mile Creek fault the rocks, which consist of Appekunny quartzites and Grinnell argillites, lie nearly horizontal along the divide; and the synclinal structure is less conspicuous. In the Graves Creek Range, just north of Lolo Creek, the Newland limestone and Spokane contacts show a north-south trending anticline on the west, paralleled on the east by a similarly trending syncline. These structures are sheared off on the south by the Lolo Creek fault and on the north by the Blue Mountain fault.

Later folds.—These structures are very irregularly arranged, are of less magnitude than the earlier folds, are nearly closed or overturned to the north or northeast in many cases, and are highly sheared. They are closely associated with the east-west trending thrust-faults and often are the results of dragging. In general, these folds trend in an east-west or northwest-southeast direction. The areas between the Eight Mile and Woodchuck Creek faults and also between the Davis and the Miller Creek faults offer excellent examples of these younger folds superimposed upon the older. In the latter area, the rocks occupy a part of the western flank of the older north-south trending syncline; and the general dip is to the southeast, as shown by the stratigraphic relations. However, the local strikes of the beds are often in a northwest-southeast direction, which also indicates the trend of the younger folding.

An overturned fold occurs just northeast of Burnt Fork Lake in the southeastern corner of the area. The overturn is toward the northeast, and the strike is nearly parallel to the underthrust faults. On the surface only the Newland limestone appears to be affected.

The limestone is highly metamorphosed, and along the understretched limb of the fold a basic dike intrudes the sheared limestone.

FAULTING

Faulting, because of the relative competency of the Belt series, is much more conspicuous in this region than folding, but, like the folding, it was produced during two periods of deformation. The first wave of deforming stresses produced thrusts along the Bitterroot Valley; the later gave rise to the more conspicuous east-west trending overthrusts and underthrusts.

In general the faults may be grouped into four separate types:

1. Overthrusts
   a) Low angle
   b) High angle
2. Wedge faults
3. Underthrusts
4. Normal faults

Overthrust faults.—Thrust faulting is the dominant type of rock failure in the region, and most conspicuous of the thrust faults are the nearly parallel overthrusts in the northern part of the area. Near the border of the Idaho batholith, west of the Bitterroot River, these overthrusts trend in nearly an east-west direction (Fig. 1). The faults farther north, however, have a trend nearly N. 50° W. The eastern extensions of all of the faults become obscured by river gravels. The thrust fault south of Lolo Creek and the Blue Mountain thrust bend southward up the Bitterroot Valley as they approach it; and the others, although obscured, may do likewise. Across the river to the east another series of faults, which may or may not be the same series of faults occurring west of the valley, has a general N.70° E. strike and extends beyond the mapped area. The western extensions of these faults, in contrast to those west of the valley, appear to meet the river more directly, instead of curving to the southward. All of the overthrust faults are not only similar in trend, but they dip southward or southwestward; and the upthrow side is always on the south. As tentatively shown in Figure 1, the overthrust faults curve gradually southward and probably connect with similar north-south trending faults within the Philipsburg

Quadrangle. The throw of the faults ranges from 2,000 to over 10,000 feet.

Of the two series of faults, only the Clark Fork overthrust and the Davis Creek overthrust are of the low-angle type. The Clark Fork fault has a low dip of 10°–25° and has thrust the Upper Belt rocks onto Paleozoic limestones. The horizontal displacement is nearly 5 miles. The Davis Creek fault, which probably is the northwesterly extension of the Philipsburg overthrust,[20] dips nearly due south in the area studied, at an angle of approximately 30°. The actual overthrust is about 2 miles. All the other overthrust faults of the series vary in dip from 50° to over 60°, and the amount of horizontal displacement is not definitely known. The Pattee Creek thrust appears to be the western extension of the Bearmouth thrust, which Pardee[21] suggests may be an extension of the Philipsburg overthrust. If this is true, the Philipsburg thrust is probably not one of the older tectonic structures of the Laramide Revolution, as suggested by Emmons and Calkins,[22] but is related in time and in genesis to the overthrusts described above.

Underthrust faults.—Whether a fault is to be considered an underthrust or an overthrust depends upon one's assumption as to the direction of the stresses that caused the breaking and whether the upthrow side is the passive or active block. All of the overthrust faults just described are assumed to have been caused by north- or northeastward-directed forces. This assumption is based on the fact that there is a lack of extreme brecciation and dynamo-metamorphism in the downthrow blocks and also because some of the later folds are overturned to the northeast. These overthrusts form the north and northeastern boundary of a synclinal wedge which, on the southwest, is bordered by the underthrusts described below.

From the Eight Mile Creek fault on the north, for a distance of 15 miles to the southward, the crest of the divide is composed of Grinnell and Appekunny quartzites. These formations are nearly horizontal with a gentle synclinal structure, and no conspicuous faulting was noticed. However, from Burnt Fork Creek southward another

[20] C. H. Clapp, personal communication.

[21] Pardee, *op. cit.*, p. 170.

[22] Emmons and Calkins, *op. cit.*, p. 146.

series of nearly parallel trending faults, which strikes about N. 50° W., is shown. The faults dip to the northeast, and the downthrow blocks are on the southwest. These faults are considered to be underthrusts, and since good evidence of underthrust faulting is present, the faults deserve individual description.

Dominic Butte underthrust.—This fault is probably one of the most interesting underthrusts described in the Rocky Mountains.[23] Its trace extends from the Rock Creek–Bitterroot divide southwestward for a distance of over 6 miles, beyond which it curves sharply to the east and then northeastward, forming a tongue-shaped loop. The width of the tongue near the crest of the divide is about 4 miles, but it narrows gradually southwestward to about 2 miles. A mass of brecciated Newland limestone, which is also highly metamorphosed, occurs on the west side of the tongue over an area more than 1½ miles in width. As shown by the depth of Gold Creek Valley, the breccia is nearly 2,000 feet thick. Many blocks up to 6 feet in diameter consisting of scapolitized, brecciated limestone and quartzite are conspicuous along Burnt Fork and Gold creeks. Some quartzite pieces 10 inches in length were found in the large blocks of limestone. Also intruding the limestone breccia are small monzonitic stocks and basic dikes. The tongue which represents the upthrow side of the fault consists of Appekunny quartzite and Grinnell argillites. These older formations show but slight disturbances and directly overlie the younger brecciated Newland limestone. A fault dipping to the northeast and striking N. 40° W. cuts the tongue in two. This fault is probably the offset extension of the older Burnt Fork underthrust. Furthermore, extending along the Sapphire divide and near the northeast extension of the tongue, three limestone bands arcuate to the northeast. These bands of limestone are extremely shattered, and a small amount of basalt float was found near the contacts. Since no other limestone members are known to be older than the Appekunny quartzites, we must infer that the Newland limestone has been underthrust beneath the Appekunny quartzite as far as the divide and that these bands, in

[23] Credit for the correct mapping of this underthrust is given to Dr. C. H. Clapp; and since he plans to publish in detail his interpretation of the structures, only the major features are given here.

some manner, have been thrust up through the older quartzites. The amount of underthrust, as measured by the offsetting of the older Burnt Fork fault, is about $2\frac{1}{2}$ miles.

Burnt Fork underthrust.—The trace of this underthrust extends from the Ambrose Greek stock on the north for 7 miles southeastward to Burnt Fork Creek. Throughout much of this distance the fault is not readily seen but is well exposed just north of the creek. Upper Grinnell argillites on the west are in contact with the Appekunny quartzites on the east; and the displacement may not be over 4,000 feet, although, just north of the junction of Gold and Burnt Fork creeks, the highly brecciated Newland limestone comprises the downthrow block. The fault dips to the northeast at an angle of about 45° and is offset $2\frac{1}{2}$ miles to the southwest by the later Dominic Butte underthrust.

Gold Creek underthrust.—This underthrust strikes about N. 50° W. and has been traced from the divide northwest of Gold Creek southeastward, where it is also cut off by the Dominic Butte underthrust. The fault dips to the northeast. Like the Burnt Fork underthrust, the downthrow side is on the southwest, and Newland limestone is thrust beneath older Grinnell and Appekunny formations.

Stony Lake ramp.—This ramp comprises a narrow block of Newland limestone, averaging $\frac{3}{4}$ mile in width, which extends from Stony Lake northwestward to the Dominic Butte underthrust. The limestone has been badly shattered, and on either side it is faulted against Appekunny quartzites. The fault plane on the southwest is clearly exposed in a cirque on the divide and dips 50° to the southwest. The fault on the northeast side of the ramp dips to the northeast and probably is the continuatiom of the Burnt Fork underthrust.

Wedge faults.—For want of a better name the faults dipping to the north and occurring within the upthrow blocks of the major overthrusts are called "wedge faults." There are at least three of these faults forming narrow wedges, 1–4 miles in width and over 6 miles in length, in the hanging walls of the Miller and Davis Creek overthrusts. The stratigraphic throw of these wedge faults is in places over 3,000 feet, but as a rule it is less.

Woodchuck fault.—Although this fault has been traced north of Woodchuck Creek to the divide, the direction of dip could not be determined. The fault differs from the overthrusts as it arcuates to the southeast; but, like them, the upthrow side is on the south. Because of considerable distortion and brecciation along the fault, it is thought to be a thrust with the plane dipping to the southeast. As seen on the map, the fault encircles the block of undifferentiated Upper Belt rocks. These formations appear to be repeated by strike faults and also by east-west striking dip faults. Exposures are too poor to give a complete picture of the complex.

Normal faults.—Little evidence of normal faulting was found, except along the front of the Bitterroot Range. Although relaxational faults are to be expected in a region which has undergone such strong deformation as this, it is not likely that their displacement would be large enough to be detected, owing to the similarity and great thickness of the formations.

In 1904 Lindgren[24] believed that the east front of the Bitterroot Range is determined by an enormous flat fault of normal character. The dislocation was thought to involve a double movement, the hanging wall having gone downward while the foot wall moved upward. The writer's evidence for normal faulting does not agree entirely with that given by Lindgren, but the general conclusion is the same. The evidence is outlined below.

An unusually regular surface forms the eastern slope of the Bitterroot Mountain, slanting 15°–35° toward the valley and extending the full length of the range. This surface is on both igneous and sedimentary gneiss, and generally conforms closely in strike and dip with the slipping planes.[25] Slickensides and striations on the surface give evidence of a movement usually parallel to the dip of the gneiss and the planes of movement. The strongest granulation and most closely massed slipping planes occur at the base of the range along the structural fronting plane. This plane extends upward to an elevation of over 8,000 feet in the area mapped. As stated by Lind-

[24] Lindgren, *op. cit.*, pp. 47–51.

[25] The displacement along the east front of the range has occurred along numerous slipping planes, with the development of a granulated gneissic zone nearly 3,000 feet in thickness.

gren, the maximum movement on the fault plane was 2 or 3 miles, and the throw between 4,000 and 6,000 feet. Evidences that the movement has been a double one are: (1) elevation of the Bitterroot Mountains 2,000 feet above the adjacent regions; (2) the depth of the valley fill, as shown by the well bore at Corvallis, where the gravels and clays extend downward at least 1,100 feet below the present valley bottom; and (3) the gradients of many of the streams, which become steeper as they near the valley.

The age of the fault is not definitely known, but that the faulting has continued to recent times is suggested by normal faulting which has occurred in the Curlew mines on the west side of the valley. Along this fault, gravels containing carbonized wood comprise the hanging wall, while the footwall is composed of pre-Cambrian quartzites and limestone. The fault dips to the east. Near the mine, actual faulting took place in 1898 along the contact of the sediments and gneiss.[26]

PROBLEM OF THE BITTERROOT VALLEY

With the more detailed field work, not only is the normal faulting postulated by Lindgren verified but the fact is established that the valley has had a far more complex history than previously supposed.

Unfortunately, few bed rock exposures are found near the Bitterroot River between the mouth of Lolo Creek and the southern boundary of the map; therefore, little knowledge of the structure can be gained from an examination of the relations of the rocks at the foot of the Bitterroot Range and those exposed across the valley 9 miles to the east. However, from Eight Mile Creek northward the width of the valley narrows to only a mile at the town of Lolo. Here the structural relations are complicated by additional faulting. Helena limestone is exposed just west of the town of Lolo, but directly across the Bitterroot River are cliffs of distorted Newland limestone, and both formations have a general eastward dip. Consequently the younger Helena limestone appears to dip beneath the older Newland limestone; and, if we assume that no great folding has occurred within the distance across the river, it is very likely that Miller Peak argillites would dip beneath the Grinnell argillites

[26] Lindgren, *op. cit.*, p. 49.

or the Newland limestone as shown in cross section *DD'*, Figure 3. Two miles farther north this relation is fairly well shown, as eastward dipping Miller Peak argillites occur both east and west of the river, and just south of Miller Creek Grinnell argillites also have an eastward dip. The probable stratigraphic throw is therefore about 15,000 feet. From these facts it must be assumed that faulting has brought the older rocks on the east side of the river over the younger formations to the west, but the definite position of the fault is not known. The throw of this inferred fault, of course, cannot be exactly measured; but it appears to be of such magnitude that it is improbable that the fault would die out before reaching the front of the Bitterroot Range. This would give a faulted relation exactly opposite to that which would be produced if the Bitterroot Valley were entirely the result of displacement along a normal fault having a low dip to the east.

Evidence that this inferred Bitterroot thrust is probably older than the east-west trending series of overthrusts is seen in the north-south trending thrust fault east of the river. This fault dips about 60° to the west and is cut off on the north by the Pattee Creek thrust fault and on the south by the Miller Creek thrust. It is probable that this north-south trending fault forms a wedge in the hanging wall of the major Bitterroot thrust. Furthermore, considerable distributary faulting which shows underthrusting from the west or overthrust from the east occurs on the west side of the valley between Lolo and O'Brian Creek. Other evidence for thrust faulting preceding the normal faulting is found in faulted relations of the argillites and Newland limestone in the xenolith north of Mill Creek previously referred to.

Besides the foregoing evidence for a Bitterroot thrust, there has been some tearing along the front of the Bitterroot Range. Although the evidence is meager, this tearing is inferred because of (1) the probable dragging of the series of overthrust faults west of the valley from an east-west or south-east trend to a more southerly trend as they approach the valley, and (2) divergence in the dip of the gneissic structure from a normal eastward or northeastward direction to a southeastward direction. If the gneiss and schist bordering the batholith had resulted from only an upward movement of the magma, the foliation of the gneiss should parallel the

periphery of the intrusion. Therefore, on the northeast side of the batholith one should expect the dip of the gneiss to vary from north to nearly east, but it should in no case dip to the southeast. The fact that most of the dips taken show an east to southeast direction at the base of the range from Carlton Creek southward to Bear Creek, while higher on the slope the dip is more often in the expected east or northeast direction, suggests a northward shoving of the west side of the valley relative to the area east of the gneissic zone.

We may tentatively summarize the structural development of the Bitterroot Valley as follows:

1. Development of the large north-south trending Bitterroot thrust fault, dipping eastward and probably contemporaneous with the upthrust faults bounding the linear ranges in northwestern Montana.

2. Batholithic intrusion within the Bitterroot Range, with contemporaneous development of the series of overthrust faults and tear faulting along the older faulted and weakened zone, together with the dragging of the gneiss and bending of the faults to the south.

3. Normal faulting. This produced, at least in part, the slickensides and a granulation of the gneissic zone by sinking of the valley and uplift of the range along the zone which had been weakened previously by thrust faulting, intrusions, and tearing.

This complex history perhaps in part accounts for the considerable subsidence of the floor in a valley so narrow that its fill, ordinarily, would be easily supported by the strength of the earth's crust.

RELATIONS OF THE STRUCTURES TO THE INTRUSIONS

There are many reasons for believing that there is a close relationship of the structures of the second episode of deformation to the Idaho batholith, as well as to the minor injections; but some of the suggestions offered are only tentative. A brief summary of these suggested relations is given below.

1. The overthrust faults are arranged concentrically about the north and northeast margin of the Idaho batholith. They dip toward it and are overthrust from it.

2. The hypabyssal rocks are very abundantly injected along the fault planes and appear to have been injected during the actual period of faulting, as some are sheared while others are little disturbed or unaffected. These dike rocks associated with the faulting are also similar in composition to the facies of the major batholith. They often are aschistic and vary in composition from tonalites to granites. However, basic monzo-gabbros also occur along the shear zones.

3. There is a relatively rapid increase in the complexity of the structures as the intrusion is approached. It therefore appears that the batholith is at the focal point from whence the forces have been directed.

4. The zone of younger gneisses and schists occupies in this region an area of nearly 150 square miles; and there is a greater development of the schistosity in the extreme northern part of the Bitterroot Range than farther south along the eastern side, which possibly indicates greater mushrooming of the batholith to the north.

5. At the base of the Bitterroot Range paralleling the valley the dip of the older gneiss seems to have been dragged slightly from its normal position. Also, the overthrust faults north of the range which can be traced nearest the river bend southward up the valley, and the others may do likewise. These factors may indicate a relatively greater northward movement of the intruded rocks west of the river than east of it.

Unfortunately, time was not available for any detailed work with the methods used by Cloos. The area, however, offers adequate exposures for very detailed examinations.

If we prefer to accept the view that the structures described above were produced by other forces than those transmitted by the batholith, areas farther from the batholith should give some record of such forces. On the other hand, if we accept the evidence suggesting relationship to the batholithic emplacement, it follows that the age of the intrusion must be late Cretaceous or early Eocene, as the overthrust faulting has been shown to cut the older structures produced in the earlier stages of the Laramide Revolution. Furthermore, since it is very probable that the Bearmouth fault and Philipsburg fault are related in age, and as these are tentatively correlated

in age and genesis with the overthrusts here discussed,[27] we have additional evidence for a late Cretaceous or early Eocene age of the latter. If the batholith is older than the thrust faulting adjacent to it on the north, some shearing within the massive granite should be present and the trend of the shear planes should correspond to the trend of the faults. Some shearing in the schlieren gneiss was noted; but these shear planes have a north-south strike, which is nearly at right angles to the trend of the overthrusts. In any case, the shearing is not conspicuous and probably only indicates that the area was still under the influence of easterly directed stresses after parts of the magma had solidified, or else the renewal of compressive stresses at a later time. On the other hand, east-west perpendicular jointing across the gneiss is abundant and would indicate, according to Grout,[28] tension or a direction of least pressure; hence a direction of motion at right angles to the joints.

Cloos's methods of investigating granite tectonics are based primarily on the assumption that magmas intrude under directed stresses. The shapes of most of the larger intrusives in folded mountain ranges seem to justify this assumption because of their elongation parallel with the folds and normal to the direction of the active forces. One would, therefore, expect a magma in process of emplacement to be somewhat analogous to a viscous solution being compressed between vise-like jaws in the earth's crust. As the western jaw moved inward, the other jaw would remain passive or move less rapidly eastward. Thus, in a region under eastwardly directed stresses, the magma would rise[29] until a definite zone in the upper crust was reached where horizontal thrusting aside of the country rocks would be easier than for the magma to rise higher. With tangential diastrophic forces one would expect the batholith in this region to thrust farther to the east than to the west, even if the pressures exerted by the upper part of the magma were only hydrostatic.

[27] C. H. Clapp, personal communication.

[28] F. F. Grout, *Petrography and Petrology* (New York: McGraw-Hill, 1932), p. 199.

[29] It is not inferred that the rise of magma was due only to horizontal pressure, as factors suggested by others for the ascension of magma are too numerous to be stated here.

As previously stated, there is evidence that considerable tearing has occurred along the Bitterroot Valley, with the probability of a relatively greater northward movement of the western side. Reason for the necessary easy horizontal relief to the north possibly may be found in the relations of the intrusion to the older Bitterroot thrust fault. This fault dips to the east or away from the batholith which has intruded on the west. The initial condition would therefore give rise to underthrusting, instead of overthrusting, if stresses were directed from the batholith. The underthrust faults in the Sapphire Range have been described. Since underthrusting is thought to be normally accomplished less easily than overthrusting,[30] although some geologists would disagree, the resultant of the radially directed stresses from the northeast portion of the batholith would be rotated to a more northerly direction, and tearing would develop along the weakened zone of the valley.

Another factor which may have aided northward thrusting of the confining rocks of the batholith is the trend of the synclinal lineament which separates the linear ranges on the north from the more complex ranges to the south. This lineament nearly parallels the northern boundary of the batholith. It probably had its origin in pre-Cambrian times[31] and apparently was a downwarp through much of Paleozoic and Mesozoic time. In other words, it was a zone of weakness; and the initial dip of the formations would facilitate overthrusting to the north or normal to the axis of the syncline.

Further evidence that the area south of this downwarped zone has probably been the active region since the development of the earlier Laramide structures is seen in the trend lines of the upthrust faults of the northern linear ranges, as shown in Figure 1. These faults, such as the Mission fault, dip to the northeast, normally arcuate to the southwest, and are the older ones of the area. Their normal trend is about N. 30° W.; but as they approach the southern area, which is highly intruded by igneous rocks, they swing rapidly eastward; and the Mission fault, which is the nearest of these major upthrusts, to the batholithic masses on the southwest, actually arcu-

[30] G. R. Mansfield, "Structure of the Rocky Mountains in Idaho and Montana," *Geol. Soc. Amer. Bull. 34* (1923), p. 272.

[31] Clapp, *op. cit.*, p. 29.

ates to the northeast. It seems very probable that this change of its trend, with a bowing-out to the northeast and essential parallelism to the later overthrust faults, may have been effected by the same stresses that produced the overthrust faults which are related to the intrusions.

The Osburn fault[32] also indicates a shift of nearly 12 miles parallel to the zone separating the linear ranges on the north from the diversely arranged group of mountains on the south. The fault, like the overthrusts north and east of the batholith, was developed later than the north-south trending structures. Unfortunately, no evidence has been found as to whether the northern area or the hanging wall on the south was the active one; but since the fault nearly parallels the Idaho batholith to the south and is clearly related to igneous intrusions, it is very probable that it is closely related in time and genesis to the overthrusts of our area, and the 12 miles of shifting along it may, in part, be the result of magmatic forces.

The writer, however, is well aware of the fact that the total displacement along these thrust faults is large and that normally the emplacement of even some of the largest igneous bodies seems to have taken place without excessive deformation of the surrounding country rocks. But even so, the most conservative student will probably find it difficult to attribute the strikingly concentric arrangement of structure around this igneous body to forces other than those of the intrusion itself. In this respect the Idaho batholith appears to be in harmony with the views of Professor Chamberlin.[33]

SEQUENCE OF EVENTS

In conclusion, the geologic events since the earlier episode of the Laramide Revolution appear to have been as follows:

1. Uplift, development of the northerly trending folds and the Bitterroot thrust fault.

2. Intrusion of the Bitterroot Range by a portion of the Idaho batholith and development of the later structures. The under-

[32] J. B. Umpleby, "The Osburn Fault, Idaho," *Jour. Geol.*, Vol. XXXII (1924), pp. 601–14.

[33] R. T. Chamberlin and T. A. Link, "The Theory of Laterally Spreading Batholiths," *Jour. Geol.*, Vol. XXXV (1927), pp. 319–52.

thrusts probably preceded the series of overthrusts (and the Dominic Butte underthrust is younger than the other underthrusts).

3. Intrusion of smaller bodies of aschistic and diaschistic hypabyssals. This gave rise in an early stage to thrust faulting, but the injections continued later than the movement along the shear planes which they intrude. The larger stocks appear to be somewhat younger than the thrust faulting.

4. Development of an old erosion surface across the later intrusives and deformed sediments.

5. Extrusions of andesite lavas, followed by a regional uplift and the development of the Tertiary lake deposits.

6. The rise of the Bitterroot Range, which appears to have continued long after the adjacent ranges became passive. The floor of the valley subsided, and has continued to do so with slipping along the bold fronting plane to the present day.

7. In Pleistocene times the higher Bitterroot Range was more heavily glaciated than the lower adjacent ranges. Melting of the ice gave rise to Lake Missoula. As shown by the well-preserved terraces on the mountain slopes, the lake disappeared very recently.

THE GWALIOR TRAP FROM GWALIOR, INDIA

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ABSTRACT

Trap is exposed at Gwalior, Morar, Barai, Paniar, Chaura, and Mo in the Gwalior State. It occurs in the Morar series as sills, dikes, and lava flows. Two types exist: a porphyritic quartz-dolerite containing some biotite, and a fine-grained basalt. In both the augite has suffered uralitization. Six chemical analyses showed constancy of composition. The values generally agree with Washington's average for the Deccan trap with the exception of the fact that the Gwalior trap is somewhat richer in alkalies. Analysis of the ferromagnesian minerals from three rocks gave ratios of magnesia to ferrous oxide which indicate that the pyroxene is richer than the corresponding rock and support the view that crystallization enriches the magma in iron contents. The helium ratios for these rocks determined by Dr. V. S. Dubey gave an average of 500 million years, which agrees with the late pre-Cambrian age of the Gwalior system.

INTRODUCTION

In recent years many important contributions have been made to the petrology of the Deccan trap period in India, but little attention has been paid to the igneous rocks of the older formations in the country. This article deals with the trappean rocks of the Gwalior system in Central India, which in its general relationship corresponds to the Animikie of North America.[1] Although the outcrops are easily accessible and are well exposed, the only available account of the area is by C. A. Hacket, who in 1870 described these trappean rocks as "diorites."[2] The present paper contains an account of the petrology, occurrences, and chemical characters of these rocks. The radioactivity and the helium[3] contents of three specimens from this area were determined a few years ago. A reference to the age of the rocks based on the helium-ratio method has been given toward the end of this article.

STRATIGRAPHY

The general sequence of rocks in the vicinity of Gwalior is given below in tabular form, together with their supposed American equivalents.[4]

[1] *Mem. Geol. Surv. Ind.*, Vol. LI, Part I (1926), p. 15.

[2] *Rec. Geol. Surv. Ind.*, Vol. III, Part II (1870), p. 39.

[3] *Nature* (November 22, 1930).

[4] *Mem. Geol. Surv. Ind.*, Vol. LI, Part I (1926), pp. 15 and 16.

The Vindhyan system (Unconformity)		Keweenawan
The Gwalior system (Unconformity)	Morar series.—Ferruginous shale, slates, hornstone and jasper with trappean rocks Par series.—Sandstones and quartzites	Animikie
Bundelkhand gneiss		Laurentian

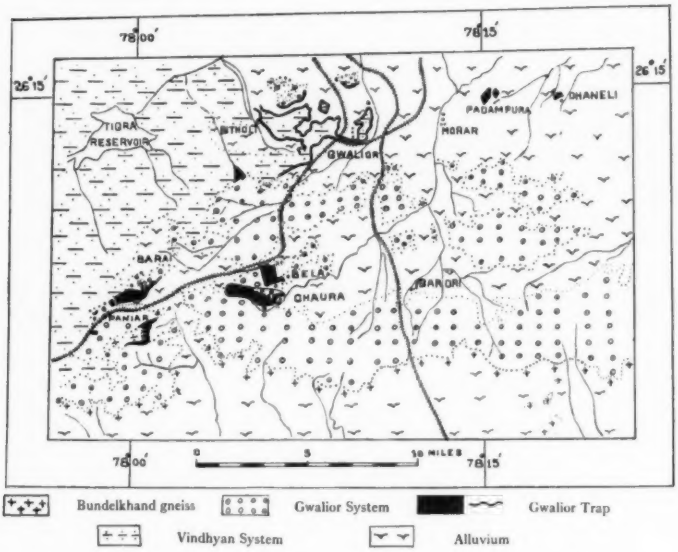

FIG. 1.—The geological map of the country around Gwalior

OCCURRENCES

Gwalior.—Of all the occurrences of trap in the Gwalior system the one at Gwalior is the most important, since the greatest thickness of the trap is seen here below the fort. The fort hill of Gwalior consists of the Kaimur sandstone (Upper Vindhyan) at the top and trap at the base. The latter can be seen all round the hill below the Kaimur conglomerate and at several places the conglomerate is absent and the trap is directly overlain by the sandstone. This se-

quence is visible for about 5 miles from the Gwalior Fort to the village of Bitholi in the west. In the hills northwest and northeast of Shankarpura[5] the section is different, the trap being overlain by the Morar series. The base of the trap is nowhere exposed.

The greatest thickness of the trap exposed below the fort is about 200 feet. Horizontal and vertical jointing were observed at several

FIG. 2.—An exposure of the Gwalior trap, Kati Ghati, Gwalior

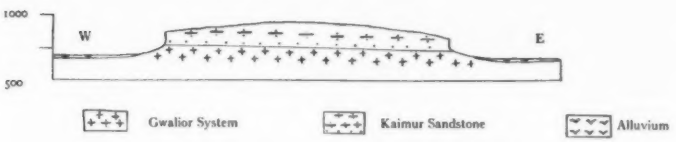

FIG. 3.—Section across the Fort Hill, Gwalior

places in this locality. The trap contains phenocrysts of feldspar visible to the naked eye.

Morar.—Near the town of Morar are several hillocks composed entirely of trap. Two such hillocks occur near the village of Dhaneli and three patches occur near Padampura.

Dhaneli.—A hill about 400 feet long, 200 feet wide, and 100 feet high rises abruptly from the Morar plains like an island. It is composed of spheroidal boulders of trap which give a very broken appearance. Half a mile northwest of this hill is a hillock showing similar characters.

[5] Long. 78°7.5′; lat. 26°14′.

Padampura.—Three patches occur near this village. One patch is a small dike running in a north-northeast–south-southwest direction and the other two form lenticular hillocks consisting of boulders of trap.

Barai.—In the vicinity of this village a prominent hill is seen with an ancient Jain temple at the top. The lower portion of the hill is composed of trap, above which lies the Morar series, which in turn is overlain by the Kaimur sandstone having a band of conglomerate at its base. West of the hill the Kaimur sandstone and the beds of the Morar series have been removed by erosion, thus exposing the trap for some distance.

FIG. 4.—An exposure of the Gwalior trap near Padampura

The total extension of the trap at this place is about $2\frac{1}{2}$ miles, excluding the detached patches that continue to the west for a distance of about 2 miles. The thickness of trap exposed in the main hill is about 50 feet. Horizontal jointing at intervals of 4 feet is seen at several places.

Paniar.—Another important occurrence of trap is found in a number of hillocks near the village of Paniar. The Morar series forms both the roof and the floor of the trap in the main hill, which is capped by the Kaimur sandstone. A hillock entirely made up of

trap and 100 feet high adjoins this hill. Other hillocks of trap are covered by beds of the Morar series ranging from 1 foot to 30 feet in thickness. The trap contains phenocrysts of feldspar.

Bela.—Here two good sections are exposed, one near Bauri[6] and the other at a point southeast of the Raipur Hill. Near Bauri the Morar series overlies the trap, the base of which is not exposed. At the other place the trap rests on the Morar series. Total extension of the trap at this spot is about 3 miles. The rock is fine grained and contains no phenocrysts of feldspar such as were noticed elsewhere.

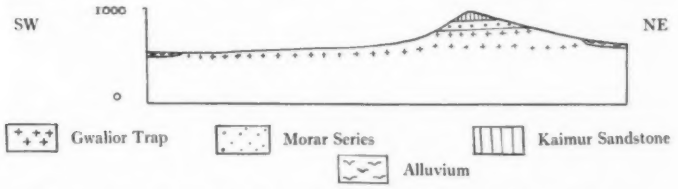

FIG. 5.—Section across the Barai Hill. (Horizontal scale: 2 inches = 1 mile)

Chaura.—A mile northwest of Chaura the trap is about 25 feet thick and lies between the beds of the Morar series. A hill southeast of the temple near Chaura is composed entirely of trap. The many fragments of jasper and sandstone found at its top are remnants of the Kaimur sandstone and conglomerate which have been denuded away. Near Nayagaon,[7] where spheroidal boulders of trap are seen lying on the Morar series, the trap extends for $2\frac{1}{2}$ miles. The greatest thickness is about 70 feet.

Mo.—Trap, overlain by the Morar group, is exposed at the base of many hills near Mo. The rock is coarse grained.

SILLS OR FLOWS

Many sections in the field show metamorphosed rocks, like hornstone and slate, associated with the trap, but it cannot be said with certainty that the metamorphism should be attributed to the thermal effect of the trap. These rocks are very common in the Morar series and, besides occurring near the trap, they also are found at places where absolutely no sign of any igneous action is seen.

[6] The Hindi word "Bauri" means a well, the water level of which can be approached by a flight of stairs built round in brick or stone.

[7] Long. 78°6′; lat. 26°7.5′.

None of the characters of lava flows have been observed in the field. The rocks at the upper junction are everywhere compact and total absence of vesicular structure is noted. Absolutely no sign of any layering or of chilled upper margins in the trap is found. No flow structure has been noticed in any of the rock sections.

All these points are in favor of the intrusive nature of the traps. Furthermore, near Padampura, the occurrence of two lenticular outcrops and of a dike of trap strongly suggest intrusions. The occurrence near Gwalior is in the line of strike of the dike near Padampura, and the rocks at these two places resemble one another

TABLE I

Occurrence		Form
Morar	Dhaneli and Padampura	Intrusions and a dike
Gwalior		Sills
Barai		Sill
Paniar		Sill
Bela		Lava flow
Chaura		Lava flow
Mo		Sill

lithologically. It is, therefore, possible that the occurrence near Gwalior is also intrusive. More evidence of the intrusive nature of trap comes from Barori, where a dike running north and south for a distance of a mile is exposed in the alluvium.

Hacket describes the occurrences of trap near Bela and Chaura as lava flows and the writer has no hesitation in supporting Hacket's views. The rocks from these places resemble each other but they differ from the rocks of the other occurrences in that they have a fine-grained texture. The fine grain favors their interpretation as lava flows. The conclusions with regard to the forms of various occurrences of trap previously discussed are summarized in Table I.

PETROLOGY

The traps vary from gray to dark gray in color and exhibit spheroidal weathering. Except at Bela and Chaura they are everywhere porphyritic. Their specific gravity varies from 2.85 to 3.04, but a large number of them (about 75 per cent) give a value of 2.97. From

a big mass rocks of two kinds are frequently obtained, one giving a higher and the other a lower value than the average specific gravity. A micrometric study of the rocks shows that the specific gravity is largely governed by the amount of magnetite or pyroxene present. Some rocks high in specific gravity also show a higher percentage of

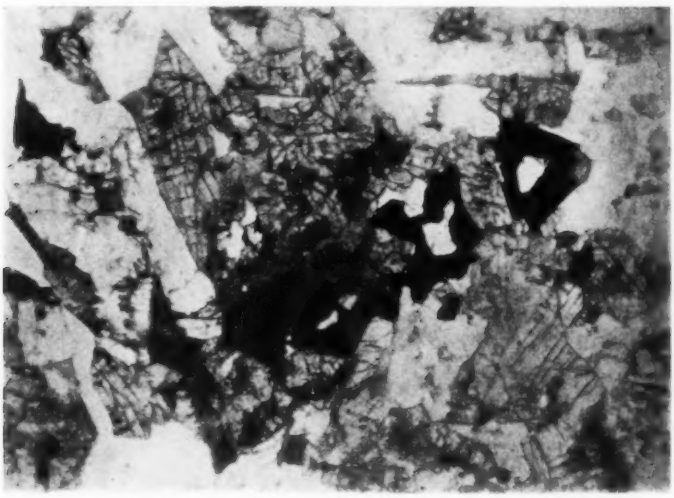

FIG. 6.—Quartz-dolerite, Padampura (illustrating the late crystallization of iron oxide).

pyroxene (see Table IV). Two types of rocks, quartz-dolerite[8] and basalt, have been identified.

Quartz-dolerite.—The mineralogical constituents are plagioclase feldspar, augite, titano-magnetite, biotite, apatite and micropegmatite. Pyrite and epidote have also been noticed in some rock sections. They are all medium-grained rocks; those from Mo are somewhat more coarse grained than the others. The plagioclase feldspar occurs both as phenocrysts and as a major constituent of the groundmass, which is holocrystalline. It forms lath-shaped idiomorphic crystals. The crystals in the groundmass are generally 1.2 milli-

[8] In this article the term "dolerite" is used in the British sense of a coarse-grained rock of basaltic composition, usually, but not always, hypabyssal. *Miner. Mag.*, Vol. XIX (1921), pp. 138–39.

meters long and show good cleavage and fine lamellar twinning. The feldspar is decomposed to kaolin and in some cases is stained by the colored decomposition products of the ferromagnesian minerals.

The augite is pale brown in color and occurs in the form of irregular plates, often 1–1.5 millimeters long. It has decomposed

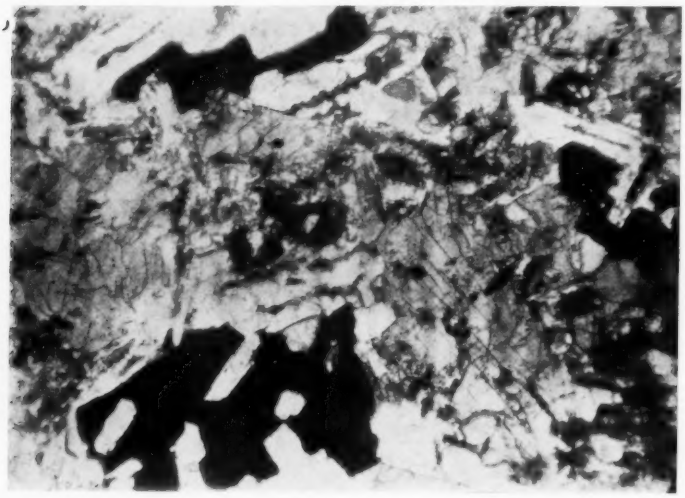

FIG. 7.—Quartz-dolerite, Dhaneli (illustrating the late crystallization of iron oxide)

to green uralite, and in some cases it has been replaced by brown pleochroic hornblende.

Patches of black iron oxide 1 mm. long and $\frac{1}{2}$ mm. wide are common, though crystals of smaller dimensions also occur. Their form is irregular. The most important thing to be noted in connection with this mineral is that it contains inclusions of feldspar and augite. Biotite is not present in all the rocks, but where it is present it has a tendency to occur at the junction of augite and magnetite or at the contact of feldspar and magnetite, suggesting that it has been formed by some kind of reaction between these minerals. Needles of apatite irregularly distributed occur in all the sections. Micropegmatite occurs in interstices. Ophitic, intergranular, and intersertal textures are extremely common.

Basalts.—No mineralogical or chemical difference is found between the basalts and quartz-dolerites, with the exception of biotite, which has not been detected in the former. They are dark gray in color, and are holocrystalline and fine grained in texture. Their occurrence in the field is confined to the two localities of Bela and Chaura. Phenocrysts of feldspar observed in the quartz-dolerites

TABLE II

CHEMICAL ANALYSES

	T/1	T/2	T/84	T/86	T/59	T/14	Average
SiO_2	51.15	49.20	49.90	50.82	50.27	49.76	50.20
Al_2O_3	12.20	11.20	11.11	13.06	11.32	11.51	11.73
Fe_2O_3	2.70	1.92	2.59	1.24	1.74	1.90	2.01
FeO	11.66	12.24	12.10	10.27	12.38	12.96	11.94
CaO	9.85	10.76	10.34	10.20	10.05	9.08	10.21
MgO	5.38	6.02	5.25	5.80	5.68	5.58	5.45
Na_2O	4.07	4.06	5.17	3.69	5.07	4.75	4.47
K_2O	.58	1.24	.84	1.01	1.06	.94	.94
TiO_2	.99	1.65	1.05	2.24	1.09	2.50	1.59
P_2O_5	.76	.47	.44	.86	.75	1.14	.74
MnO	.36	.45	.75	.48	.38	.56	.49
H_2O+	.24	.17	.20	.19	.26	.16	.81
H_2O-	0.46	0.78	0.75	0.67	0.49	0.52	
Total	100.40	100.16	100.49	100.53	100.54	100.36	100.58
S.G.	3.02	2.49	2.94	2.97	3.00	3.01	2.98

T/1 Quartz dolerite from a small hill northwest of Dhaneli
T/2 Quartz dolerite, Barai
T/84 Quartz dolerite, east of Mo
T/86 Quartz dolerite, near Mo
T/59 Quartz dolerite, Paniar
T/14 Basalt, Bela
Analyst, M. P. Bajpai

at other places do not occur at these localities. These rocks are non-porphyritic.

Alterations.—The pyroxene and the feldspar in these rocks have been much altered to uralite and kaolin respectively. In the pyroxene, the uralite is developed principally on the sides and along the cleavages. In the rocks from Mo the pyroxene has changed into brown pleochroic hornblende. Some crystals of the pyroxene have been completely replaced by this brown hornblende.

CHEMICAL CHARACTERS

Table II gives the results of chemical analyses of five quartz-dolerites and one basalt. The table shows that in spite of textural

and mineralogical variations little difference is found in the chemical composition of these rocks. The percentage of silica is fairly constant, varying from 49.20 to 51.15, and so are also the percentages of the other constituents. In alkali slight variations occur, but the total of K_2O and Na_2O is almost the same in all cases. TiO_2 varies from 0.99 to 2.55 and P_2O_5 from 0.44 to 1.44 This slight variation of TiO_2 and P_2O_5 may be due to local concentration of titanomagnetite and apatite respectively. The analyses suggest that all the various

TABLE III

NORMS

	T/1	T/2	T/86	T/84	T/59	T/14
Orthoclase	3.34	7.23	6.12	5.00	6.12	5.56
Albite	36.15	23.06	31.44	29.87	26.20	35.11
Anorthite	10.56	8.62	17.24	4.73	5.00	10.01
Nepheline	1.99	6.25	.....	7.38	9.09	.....
Diopside $CaO\ SiO_2$	13.69	17.17	11.60	16.36	17.40	11.72
Diopside $MgO\ SiO_2$	5.90	7.40	5.60	6.80	7.30	4.40
Diopside $FeO\ SiO_2$	7.79	9.77	5.81	9.77	10.16	7.52
Hypersthene $MgO\ SiO_2$	.....	.....	2.00	.....	.....	1.30
Hypersthene $FeO\ SiO_2$	.....	.....	1.98	.....	.....	2.24
Olivine $2\ MgO\ SiO_2$	5.32	5.23	4.76	7.14	4.76	3.92
Olivine $2\ FeO\ SiO_2$	7.75	7.75	5.51	4.48	7.34	7.14
Magnetite	3.94	2.55	1.86	3.71	2.55	2.78
Ilmenite	1.98	3.04	4.26	2.28	2.13	4.71
Apatite	.82	1.34	2.02	2.69	.98	2.69
Water	0.70	0.95	0.86	0.75	0.75	0.68
Total	99.83	100.45	101.06	100.98	99.78	99.78

occurrences of the trap have been derived from the same magma of a constant chemical composition. The slight chemical difference may be explained as previously indicated.

GEOMETRICAL ANALYSES

Table III shows the mineralogical composition of the rocks as studied in different rock sections with the help of a Shand's recording micrometer. It will be seen that the amount of augite in the majority of cases is approximately 40 per cent by volume and that of the feldspar is about 50 per cent. Magnetite and biotite together form about 10 per cent of the rock. In a few specimens the amount of pyroxene has reached 50 per cent by volume, but that of feldspar

has decreased to 40 per cent. A concentration of magnetite, where its amount approaches 10 per cent, is found in some of these rocks. The amount of biotite ranges from 0 to 5 per cent. It is not possible to explain the unusual richness of augite and magnetite in some rocks until each mass is studied in sufficient detail, though it is probable that crystal sinking may account for the abnormal increase of these

TABLE IV

QUANTITATIVE MINERAL ANALYSES OF THE ROCKS BY VOLUME

Specimen No.	T/1	T/2	T/86	T/36	T/17	T/49	T/7	T/83	T/23	T/48
Augite	43.92	39.52	39.62	52.8	50.66	41.77	53.46	43.97	41.30	41.01
Feldspar with micropegmetite*	50.06	50.56	54.48	40.22	46.09	45.40	37.64	45.71	51.20	49.31
Magnetite	3.89	7.39	5.61	6.3	4.27	10.25	6.70	7.16	7.38	6.00
Biotite	2.30	3.98	2.95	nil	nil	3.00	3.00	5.00	1.96	3.42
Total	100.17	99.77	102.66	99.32	101.02	100.52	101.12	101.84	101.84	99.74
Rock	Quartz dolerite	Quartz dolerite	Quartz dolerite	Basalt.	Basalt.	Quartz dolerite	Quartz dolerite	Quartz dolerite	Quartz dolerite	Quartz dolerite
Form	Intrusion	Sill	Sill	Lava flow	Lava flow	Sill	Sill	Sill	Sill	Sill
Locality	Dhaneli	Barai	Mo	Chaura	Chaura	Barai	Gwalior	Mo	Gwalior	Barai
Specific gravity	3.02	2.94	2.97	3.00	3.04	2.97	3.00	3.00	3.00	3.00

* Specimen Nos. T/36 and T/37 do not contain micropegmetite and biotite. Analyst, M. P. Bajpai.

minerals of high specific gravity. The table shows that the rocks which are very rich in magnetite are not necessarily rich in augite.

CHEMICAL NATURE OF THE PYROXENE

The pyroxene occurring in these rocks was separated by means of heavy liquids and analyzed. The results are given in Table V.

These three analyses show that the pyroxene does not have a great variation in SiO_2, CaO, and MgO. The variable constituents are Fe_2O_3.

The composition of the pyroxenes as calculated in terms of their molecular formulae is given in Table VI.

C. N. Fenner[9] is of the opinion that in the advanced stages of crystallization of a basaltic magma, the melt becomes rich in iron. According to him the crystallization of pyroxene rich in magnesian metasilicate leaves the magma rich in ferrous compounds so that, as a result of differentiation, a large part of FeO remains in the melt.

[9] *Amer. Jour. Sci.*, 5th ser., Vol. XVIII (1929), pp. 225–53.

Besides other evidences, this hypothesis is based on the ratio of MgO to FeO in augite and in the rock containing it. Fenner finds that the ratio of MgO to FeO in the augite is higher than that of MgO to FeO in the rock containing it, proving that as a result of

TABLE V

ANALYSES OF THE PYROXENE OCCURRING IN THE GWALIOR TRAP

	T/86	T/2	T/59
SiO_2	48.41	50.45	50.48
Al_2O_3	4.08	7.07	.94
Fe_2O_3	1.20	2.03	.82
FeO	16.90	14.60	20.87
CaO	13.87	11.03	12.58
MgO	10.41	10.35	12.60
Na_2O	1.95	1.94	N.D.
K_2O	.32	.40	N.D.
H_2O	.65	.50	N.D.
TiO_2	1.30	1.05	.03
MnO	0.72	0.59	N.F.
Total	99.81	100.01	99.32

TABLE VI

MOLECULAR FORMULAE OF THE PYROXENE

Molecules	T/86	T/2	T/59
Diopside-Heden-burgite	60	60	52
Clino-hypersthene	32	30	44
Acmite	1	4	.....
$Na_2O\ SiO_2$	3	.....	.....
$(AlFe)_2O_3$	4	6	2
Total	100	100	100

crystallization the relative proportion of FeO to MgO must increase in the melt.

With a view to testing this hypothesis, the pyroxenes occurring in the Gwalior trap were analyzed after separation from their respective rocks by means of heavy liquids, and the results of analyses are tabulated in Table V.

Table VII shows that the ratio of MgO to FeO in augite is higher than the MgO/FeO ratio in the rock as a whole. It has already

been made clear that the magnetite is of late crystallization. The late crystallization of magnetite and the lower MgO/FeO ratio in the rock than in the constituent pyroxene give support to the hypothesis of Fenner that the basaltic magma on crystallization becomes rich in iron.

TABLE VII

Specimen No.	$\frac{MgO}{FeO}$ in Augite	$\frac{MgO}{FeO}$ in Rock	$\frac{\frac{MgO}{FeO} \text{ in Augite}}{\frac{MgO}{FeO} \text{ in Rock}}$
T/86	0.58	0.51	1.14
T/2	.63	.41	1.47
T/52	0.59	0.40	1.47

TABLE VIII

	1	2	3	4	5	6
SiO_2	50.20	49.68	50.52	51.22	48.74	47.02
Al_2O_3	11.73	12.95	13.76	13.66	11.52	12.46
Fe_2O_3	2.01	3.47	3.87	2.84	5.71	5.80
FeO	11.94	10.10	8.50	9.20	7.16	9.25
CaO	10.21	10.09	9.09	6.89	10.83	9.90
MgO	5.41	5.69	5.42	4.55	7.25	4.51
Na_2O	4.47	2.27	2.42	4.93	3.45	4.92
K_2O	.94	.52	.96	.75	.70	1.50
$H_2O(-)(+)$	.81	2.00	2.27	1.88	2.70	1.54
CO_2	.....	.....	.58	.94	.....	.....
TiO_2	1.59	2.60	2.39	3.32	1.07	2.56
P_2O_5	.74	.33	.26	.29	.53	.69
MnO	0.49	.20	.16	0.25	0.17	0.19
Inclusions	.....	0.04	0.11	.....	.....	.....

1. Average Gwalior trap, mean of six analyses. M. P. Bajpai.
2. Average Deccan basalt, H. S. Washington's analyses, 4, 12, 13, 15, 15, 16, 23 in *Bull. Geol. Soc. Amer.*, Vol. XXXIII (1922), p. 774.
3. Average Whin Sill type mean of six analyses, H. F. Harwood. *Miner. Mag.*, Vol. XXI (Sept., 1928), p. 539.
4. Average Spilite. *Geol. Mag.*, Vol. LXVII (1930), p. 9.
5. Alkali-rich Basalt. Dhanti, Kathiawar, V. S. Dubey (unpublished).
6. Alkali-rich Basalt. Pavagad, V. S. Dubey (unpublished).

GWALIOR MAGMA TYPE AND ITS COMPARISON WITH OTHER TYPES

Table VIII shows that the Gwalior magma is similar to that of the plateau basalt of Washington in all its constituents except al-

kali, which is higher than in the Deccan trap and in the Whin Sill type. It has affinities with the spilitic suite, the soda molecule predominating over the potash molecule. In the spilitic suite CaO is considerably less than that in the Gwalior trap, with the result that the plagioclase in spilite is more sodic than that in the latter. Dr. V. S. Dubey's[10] analyses of two alkali-rich basalts from Kathiawar and Pavagad belonging to the Deccan trap age compare well in chemical composition with that of the Gwalior trap.

The rocks studied in this article are confined to a very small area compared with the extension of lavas of this age in other parts of India, and the chemical composition of the contemporaneous lavas occurring elsewhere in the country is not known. In the absence of this knowledge it cannot be said definitely whether or not the Gwalior rocks are typical of the volcanic activity of this period. It is possible that other occurrences may show a nearer approach to the typical plateau basaltic magma and that the Gwalior trap may represent an alkali-rich phase similar to that of the Deccan trap in Kathiawar.

RADIOACTIVITY

The radioactivity of these rocks was determined by Dr. V. S. Dubey at Vienna by the solution[11] method. The rock was brought into solution and the emanation developed in a definite amount of time was measured by carrying it over into an ionizing chamber fitted over and connected with an electroscope. The rate of discharge was noted. The electroscope was already calibrated by a known radium solution. The amount of helium[12] in the rock was determined by Dr. K. W. Peterson in Professor Paneth's laboratory in Königsberg. The object of the author was to determine the effect of texture on the retentive capacity of a rock for helium. The results[13] show that the maximum value of helium is obtained for the fine-grained trap from Bela Ki Bauri.

[10] I am thankful to Dr. V. S. Dubey for permitting me to publish his two analyses of alkali-rich basalts from Pavagad and Kathiawar, which he analyzed in the geological laboratory of the Imperial College of Science and Technology in London.

[11] Oral communication. [12] Dr. V. S. Dubey, *Nature, op. cit.*

[13] "Physics of the Earth," Part IV, "The Age of the Earth." By the Subsidiary Committee on the Age of the Earth. *Bull. of the National Research Council, No. 80* (1931), p. 415.

The helium ratio based on the rock gives an age of 500 million years which must be regarded as a minimum. The result is in general agreement with the known late pre-Cambrian age of the Gwalior series.[14]

[14] Acknowledgments.—The author wishes to record his sincere thanks to Professor K. K. Mathur for his valuable suggestions and advice in the preparation of this article, to Dr. V. S. Dubey for his guidance in the field and in the analytical work, and to Mr. Govardhan Das Jha, of the Department of Geology and Mining of the Gwalior State, for providing camping facilities in the field.

THE PHYSIOGRAPHY OF MAINE

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ABSTRACT

The state of Maine may be separated into four physiographic subdivisions. The largest of these, the Moosehead Plateau, is bounded by an escarpment extending across the state. The presence of this escarpment is demonstrated by a series of profiles with an accompanying discussion.

LOCATION

The state of Maine lies within the New England–Maritime province of the Appalachian Highlands. This province includes most of New England, Nova Scotia, New Brunswick, and all of Quebec southeast of the St. Lawrence River.

It has been the custom of some writers to consider the New England–Maritime province as a part of the Laurentian peneplain. This view seems incorrect, as the two provinces are separated by the St. Lawrence fault, which establishes a definite boundary between the pre-Cambrian rocks of the Canadian Shield and the Paleozoics of the New England–Maritime region. The idea apparently arose from the former tendency to regard the great bulk of the rocks of northern New England as of pre-Cambrian age. But increasing knowledge of the rocks shows them to be largely Paleozoic,[1] although they include much crystalline rock of both igneous and sedimentary types which may be older.

The eastern townships of Quebec, however, may be properly considered as belonging to the New England–Maritime province, since they consist of Paleozoic rocks which have been moderately folded with pre-Cambrian rocks outcropping in the axes of the anticlines, as in the case of the Megantic anticline, a structure which seems to merge with the folds of the White Mountains and the Green Mountains. This New England–Maritime province may be considered as an upland which has been strongly dissected since the uplift of the peneplain which gained its greatest development in Northeastern

[1] Marland P. Billings, "Paleozoic Age of the Rocks of Central New Hampshire," *Sci.*, Vol. LXXIX (1933), pp. 55–56.

North America in the Tertiary period. Sloping gently upward to the Maine border, the peneplain in southeastern Quebec forms a watershed, on one side of which the drainage passes into the Atlantic via the St. Lawrence, and on the other side into the Gulf of Maine, by the St. John, Penobscot, and Kennebec rivers.

PHYSIOGRAPHIC SUBDIVISIONS

The state of Maine may be separated into four subdivisions (Fig. 1). The first of these, which is termed the Coastal Lowlands, comprises a belt of nearly level country fringing the coast and extending inland a distance which varies from about 20 miles on the southern border to approximately 70 miles in the northeastern part of the state. This region has an average elevation of little over 100 feet above tide. Farther inland and separated from the Coastal Lowlands by a boundary which is quite evident in the southeastern part of the state, but which is less apparent as one goes north, is a belt of rolling land which comprises the Central Uplands. As a whole the Central Uplands average little over 500 feet above sea level, although areas may be found in which the elevations are markedly higher. This subdivision, which extends into New Hampshire on the south, may be followed nearly to the northeastern border of the state where it merges with the Coastal Lowlands.

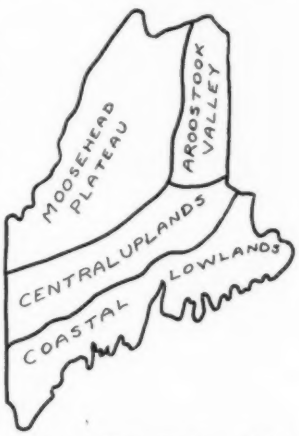


FIG. 1.—Physiographic subdivisions of the state of Maine.

West of a line extending from the New Hampshire border to the international boundary, near the confluence of the Fish River and the St. John, is a region including about one-third of the state, named the Moosehead Plateau by Perkins and Smith,[2] from Moosehead

[2] E. H. Perkins, "Contributions to the Geology of Maine, No. 2, Part I. The Moose River Sandstone and Its Associated Formations," *Amer. Jour. Sci.*, 5th ser., Vol. X (1925), p. 371; E. S. C. Smith, Part II, "The Igneous Rock of Mt. Kineo and Vicinity," *ibid.*, p. 438.

Lake, its most prominent natural feature. This area, which is the third physiographic subdivision of the state, is one of topographic unity; it averages about 1,000 feet in elevation.

A fourth region, for which the writer proposes the name Aroostook Valley subdivision, from the Aroostook River, of which it forms the

FIG. 2.—The coastal lowlands

FIG. 3.—The central uplands

drainage basin, is bounded on the west by the Moosehead Plateau, on the north and east by the St. John River, and on the south by the divide between the watersheds of the Aroostook and Penobscot rivers. It is a region of subdued topography, and has a maximum elevation of about 700 feet above sea level in its northern part.

GEOLOGY

A glance at a map of the Maine coast will show at once the complete absence of a coastal plain. The Maine coast is a typical shore

line of recent submergence. The gentle angle at which the land passes under the sea, the rarity of wave-cut cliffs on a coast which is in great part exposed, and the infrequency of bayhead and other types of beaches all point toward this. The lack of a coastal plain is explained by the fact that the present shore line is formed by the edge of a former upland. D. W. Johnson[3] has interpreted the Gulf of Maine as a drowned inner lowland fronted by a submerged cuesta which forms part of the series of "banks" which stretch from the Grand Banks of Newfoundland to the Island of Nantucket. This submergence he believes to have taken place at the end of the Tertiary or even later.

FIG. 4.—The Moosehead Plateau

Another impressive feature of the Maine coast is the sharp contrast between the regular shore line south of Casco Bay and the deeply indented coast north of it. The rock structure along the edge of the former upland apparently has determined the outline of the coast. In the south, where the strike of the rocks parallels the sea, the shore line is almost straight; the occasional bays are small, and the rivers which rise on the lowlands are rather short. In this region the few islands are nearly parallel with the shore. North of the city of Portland a very different condition is encountered. Here the rocks strike sharply away from the coast, and a ragged shore line, with many deep bays and numerous long, narrow estuaries results. Johnson[4] states that these estuaries represent drowned valleys incised in

[3] *The New England–Acadian Shoreline* (New York, 1925). [4] *Ibid.*

belts of weak rock, and Hobbs[5] describes them, specifically those of the Penobscot and Kennebec, as fault-line valleys. After examination of several of these valleys, the writer prefers the interpretation of Johnson.

In many of the older works on geology, the coast of Maine is described as a "fjord coast." More detailed study by Johnson, and others, has shown that this view is an incorrect one, the only true fjord being Somes Sound on Mount Desert Island. Examination of the valleys reveals their walls as lower and less steep than those of true fjords. The common form is that of the typical V-shaped river valley, the U-shape of the characteristic glacial trough seldom appearing. Further evidence appears in the direction of the ice movement as determined by striae. Katz[6] found that the trend of the ice in the vicinity of Casco Bay varied from true south to south 25° east, and the valleys run northeast-southwest. Most of those who have studied the geology of the Maine coast believe the ice to have done little more than modify the topography to a limited extent. This view is held by George Otis Smith and E. S. Bastin.[7]

TOPOGRAPHY

The Coastal Lowlands are distinguished by their monotonous similarity. The region presents the characteristics of a peneplained oldland sloping gently toward the sea. Though some low mountains, or groups of mountains, such as Blue Hill, the Camden Hills, Tug and Lead Mountains in the vicinity of Machias, rise for a few hundred feet above the surrounding country, the dominant note is one of flatness; the average elevation is not more than 100 feet. In general, the demarkation of the coastal region from the Central Uplands is not sharp. It consists of a more or less gentle slope which may be traced with relative ease in the region of York and Cumberland counties, but which is progressively less distinct farther north until in the Grand Lake region of Washington County, where the

[5] W. H. Hobbs, "Lineaments of the Atlantic Border Region," *Geol. Soc. Amer. Bull. 15* (1904), pp. 483–506.

[6] F. J. Katz, "Geology of Portland and Casco Bay Quadrangles," *3d Ann. Rept., Maine State Water Commission* (1912), p. 179.

[7] George Otis Smith, E. S. Bastin, and C. W. Brown, "Penobscot Bay Folio, Maine," *U.S. Geol. Surv. Atlas, No. 149* (1907).

Lowlands attain their greatest width, its location is more or less arbitrary.

The Central Uplands consist of a belt of gently rolling country with an average width of about 40 miles, extending in a northeasterly direction from the southern boundary of the state until it merges with the Lowlands along the gentle divide which separates the Penobscot drainage from that of the Machias River of Washington County. This zone which follows closely the prevailing strike of the rocks, is a peneplained oldland which has been uplifted and tilted toward the east. The uplift has caused a partial rejuvenation and a considerable degree of dissection, although the region is composed almost entirely of resistant metamorphic rocks. Though the Uplands have a somewhat uneven topography, most of the numerous hills are low and commonly present a gentle aspect on all sides. There are some steep cliffs, due to glacial plucking. A few monadnocks rise above the general level of the region; as examples, Pleasant Mountain in the town of Denmark, Mount Blue in Avon, and Mattamiscontis in the Schoodic Lake region may be cited. In most cases these monadnocks represent intruded masses of igneous rock which have been exposed by the peneplanation of the land. The Central Uplands are separated from the Coastal Lowlands by the gentle slope described, and from the Moosehead Plateau by a more distinct escarpment. As in the other regions, these boundaries grow less distinct toward the northeast, the subdivisions merging gradually into each other.

The third physiographic subdivision, the Moosehead Plateau, comprises the incised remnant of the Tertiary peneplain which formerly covered northeastern North America. This region, the northwestern third of the state, is an area of rolling land which includes most of the "Maine woods" country, known to the sportsman and lumberman. North of Moosehead Lake lies a wilderness nearly 200 miles in length, and half that in width, uncrossed by a single motor road, and almost uninhabited. It forms the drainage basin of the state's principal river, the St. John, and its chief tributary, the Allegash. The area was uplifted after its peneplanation, and has been considerably dissected. The larger rivers have incised their valleys from 500 to 600 feet below the general level of the plateau. With the ex-

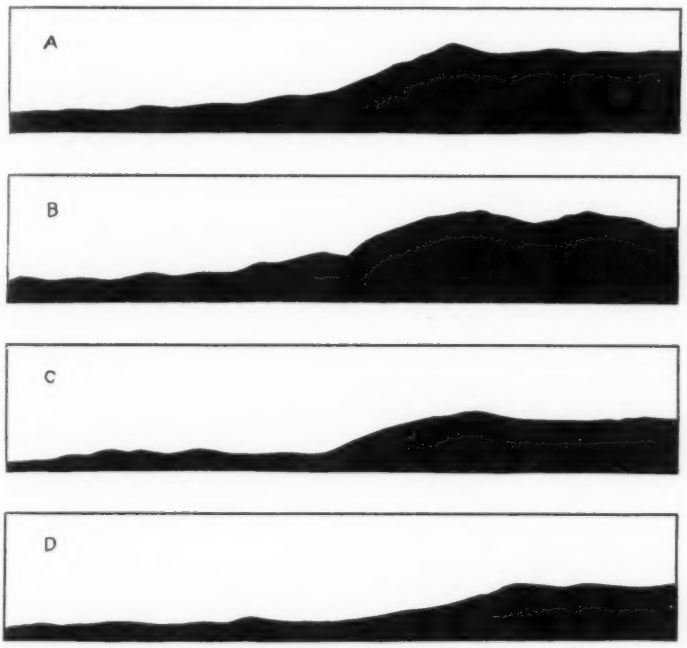
ception of these valleys, the Moosehead Plateau is a typical peneplain with the summits of the hills and low mountains noticeably accordant. From these moderate elevations many hundreds of square miles of nearly level country may be seen with here and there a monadnock rising from 1,000 to 2,000 feet above its surroundings. All of the higher mountains of Maine rise from the plateau. The highest of these, Mount Katahdin, with an elevation of 5,268 feet, lies at its eastern edge.

The Moosehead Plateau is separated from the Central Uplands by a definite though somewhat eroded escarpment, resembling the Allegheny Escarpment of east central New York. This escarpment may be traced in a northeasterly direction across the entire state, its presence being clearly shown by a series of profiles accompanying this article. These profiles have been constructed from railroad surveys, since a large part of northern Maine has never been mapped topographically. In several unmapped areas the presence of the escarpment is demonstrated by rapids or falls, in some cases of considerable height, formed where the youthful streams flow southeastward off the plateau. The nature of the escarpment varies widely; in the southwestern part of the state it may be readily traced in the field trending somewhat east of north. To the north of Mount Katahdin, the edge of the plateau has been post-maturely dissected to a much greater extent; here the escarpment is less noticeable. It may, however, be traced on the available topographic maps as a serrated line running nearly northward until it reaches the Canadian border, a short distance west of the point where the Fish River enters the St. John.

Although the Moosehead escarpment follows the general northeast trend of the Maine formations, little local relation exists between it and the underlying rocks. Not only does the escarpment fail, in most cases, to follow geologic boundaries; it passes across many different types of bedrock, showing only slight evidences of structural control. Study of the recent *Preliminary Geologic Map of Maine*[8] shows that in only two instances does the escarpment coincide with formation boundaries. In the central part of the state it

[8] Arthur Keith, *Preliminary Geologic Map of Maine*. State of Maine Geol. Surv. (Augusta, 1933).

follows the edge of the Katahdin batholith for a number of miles. In northern Aroostook County the escarpment is apparently determined by the Devonian-Silurian boundary for a distance of perhaps 10 miles across the Winterville quadrangle, although a few miles to



Vertical scale (all profiles) 1 in. = 1600 ft.
Horizontal scale (all profiles) 1 in. = 6 mi.

FIG. 5.—(*A*) Profile of Maine Central Railroad, Peru to Oquossoc; (*B*) Sandy River and Rangeley Lakes Railroad, Farmington to Rangeley; (*C*) Maine Central Railroad, Oakland-Kineo Division, North Anson to Lake Moxie; (*D*) Bangor and Aroostook Railroad, Southern Division, Derby to Greenville.

the south it passes obliquely across the belt of Devonian rocks. It is probable that the escarpment originally followed the contact, which runs northeast to the Canadian border, but post-mature erosion has shifted it a number of miles to the westward, leaving a much dis-

sected "border zone" between the plateau and the flat lands of the upper Aroostook Valley.

The course of the escarpment from the New Hampshire line to the immediate vicinity of Mount Katahdin is nearly northeast, with a few local deviations. From this point to the Canadian border the edge of the plateau trends almost due north.

The Moosehead escarpment appears a short distance west of the New Hampshire–Maine border, on the southern edge of the city of Berlin, New Hampshire, as a distinct rise on the road which leads thence from the town of Gorham. From this point its course across Oxford and Franklin counties, Maine, is somewhat difficult to trace in detail, as it crosses three unmapped quadrangles in a region where field observation is extremely difficult. Its presence is, however, convincingly demonstrated by the series of railroad profiles presented. The edge of the plateau is particularly well shown on the profile of the branch of the Maine Central Railroad (Fig. 5A) between Peru and Oquossoc; the line climbs from the Central Lowlands, rising 700 feet in a distance of 18 miles, the last few miles very steeply. The first mapped quadrangle crossed by the escarpment is the Phillips quadrangle; here it appears plainly, causing a definite change of level of nearly 1,000 feet. It is clearly shown on the accompanying profile of the Sandy River and Rangeley Lakes Railroad (Fig. 5B) between Farmington and Rangeley. The escarpment thence crosses the extreme northwestern corner of the Kingfield quadrangle, the southeastern corner of the Dead River quadrangle, and, still trending northeast, the western portion of the neighboring Bingham quadrangle. A short distance west of the Kennebec River it swings sharply to the southeast across that river and into the unmapped quadrangles between Bingham and the vicinity of Mount Katahdin. Throughout this portion the edge of the plateau may be recognized in the field as a steep descent on the road which runs from Bingham to Abbot Village, and as a prominent ridge on the skyline to the northward. The escarpment also appears on the profiles of the Maine Central Railway from North Anson to Lake Moxie (Fig. 5C) and of the southern division of the Bangor and Aroostook Railroad between Derby and Greenville (Fig. 5D). It follows the southeastern

edge of the Katahdin batholith for a number of miles in the region just south of Mount Katahdin, and crosses the west branch of the Penobscot River at Ripogenous gorge about a mile below the foot of Ripogenous Lake. At the extreme southeast corner of the Katahdin quadrangle the edge of the plateau swings sharply to the north, a direction it follows with little deviation from this point to the Canadian border.

The course of the escarpment across the two unmapped quadrangles to the north is demonstrated in the field by the changes in gradient of the streams which cross it. Two of these changes, the Grand Falls on the east branch of the Penobscot, and Godfrey's Falls on the Seboeis River, are of considerable height; at the former the east branch of the river drops 40 feet in a nearly vertical fall, and in the latter case a vertical fall of about 60 feet marks the escarpment. About 15 miles to the north a noticeable change in gradient produces the only rapid to be found in many miles along the course of the Aroostook River and marks the point where that river crosses the escarpment, about a mile above its junction with Mooseluck stream. A few miles to the north is the Greenlaw quadrangle, in the extreme western part of which the escarpment occurs. Thence it is continuous through the Winterville and Eagle Lake quadrangles to the border, which crosses it a short distance west of the village of Fort Kent at the mouth of the Fish River. Throughout this latter part of its length the edge of the plateau appears as a ragged escarpment which has been eaten back by post-mature erosion producing the "border zone" previously mentioned. The portion of the escarpment which coincides with the Silurian-Devonian boundary lies within the township of Winterville and is about 5 miles in length; south of this point it passes obliquely across the belt of Devonian rocks, showing a complete absence of control by the underlying structure.

DRAINAGE

The drainage of the state of Maine shows many of the characteristics of a recently glaciated region. Sharply divided drainage basins, and valleys which are still in youth throughout most of their

length, are to be found. Some of the valleys are mature in their lower parts, but flood plains, meanders, and oxbow lakes are rare. The typical Maine river valley is narrow and steep sided in its upper reaches and broadens but little as the sea is neared. Rapids and even falls of considerable size are common throughout nearly its entire length and the current is seldom slow. Abrupt changes in direction are common; many of the rivers follow their preglacial courses for some distance only to leave them abruptly where the original channels were blocked by Pleistocene ice or drift dams. One result of the glaciation has been the creation of an extremely large number of lakes and ponds which serve as storage basins and insure a much more even run-off than would otherwise prevail. These lakes and ponds, which in most cases lie in glacially dammed and over-deepened valleys, range in area from a few acres to that of Moosehead Lake, 115 square miles. The ratio of water area to land area in the basin of the Kennebec[9] is 1 to 14.

Perkins[10] has shown, in a carefully worked-out study of the Waterville region, the existence there of several clearly defined drainage levels similar to Barrell's piedmont terraces. They are found both on the Coastal Lowlands and the Central Uplands.

Striking testimony to the youth of the Maine drainage is found in the postglacial rock gorges which occur in several localities; perhaps the most impressive of which is the picturesque gorge on the west branch of the Penobscot River immediately below the Great Northern Paper Company's storage dam. The water rushes through a narrow gorge cut in resistant quartzite and Katahdin granite; this gorge in some places is 70 feet deep; throughout its length the walls are almost vertical. The main gorge is $1\frac{1}{2}$ miles in length, and the series of abrupt rapids every few miles between its foot and the head of the Lower Lakes are further evidence of the youthfulness of the channel. Another considerable postglacial gorge is on the Saco River 15 miles above its mouth, where the river has incised a gorge $\frac{1}{2}$ mile

[9] H. K. Barrows, "Water Resources of the Kennebec River Basin," *U.S. Geol. Surv. Water Supply Paper* (1907), p. 198.

[10] Edward H. Perkins, "Contributions to the Geology of Maine, No. 3. The Evolution of the Drainage of the Waterville Region," *Amer. Jour. Sci.*, 5th ser., Vol. XIV (1927), pp. 352–64.

long in the steeply dipping Berwick gneiss. It has a maximum depth of 60 feet and a width of 30 feet, and is asymmetric in cross section; the north side is generally precipitous, but the south side, following the dip of the gneiss, slopes at an angle of 55°. The occurrence of such a gorge so near the sea is particularly striking. A third example is found in the steep-walled gorge of Pleasant River, a mile in length near Katahdin Iron Works. Several minor gorges are noticeable in the channel of the east branch of the Penobscot River below the "Grand Falls."[11]

[11] The writer is indebted to Professor Edward S. C. Smith for counsel during the preparation of this paper, and to Mr. Henry W. Dill, Jr., for drawing the profiles.

TERMINOLOGY OF SURFACE FORMS OF THE EROSION CYCLE

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ABSTRACT

The present lack of uniformity and precision in the use of terms applied to surface forms of the erosion cycle makes evident the need for a revision and simplification of the system of nomenclature. In the following article the writers review the concept of the erosion cycle and propose a logical terminology applicable to the humid and the arid cycles of erosion. Some of the terms now in use are redefined and a few new ones are suggested.

THE HUMID CYCLE

The general concept of sequence of land forms in a naturally progressive cycle of erosion as outlined by William Morris Davis[1] fifty years ago has been greatly elaborated by him and by other physiographers. The development of nomenclature of surface forms has been the normal accompaniment of these further studies. During this period of growth, lack of uniformity in usage and inexactness in definition of some terms has caused confusion. In this article the writers propose a simplification and redefinition of several terms used in correlating age and stage in the cycle with accompanying surface form. They likewise suggest introduction of a few new terms to make more nearly complete the system of nomenclature now in use in describing the typical humid cycle and the special arid cycle of the Basin and Range province of the western United States.

Davis, in his original scheme, envisaged the reduction in a humid climate of an uplifted land surface of low relief. The similarity between the different stages of the cycle of erosion and those of human life was early recognized and an analogy pointed out. The quickening of stream activity and development of strength of relief suggested adolescence and early maturity. The progressive reduction of relief and weakening of stream erosion suggested the changes which take place in man in later maturity and old age. The feeble-

[1] "Geographic Classification, Illustrated by a Study of Plains, Plateaus, and Their Derivatives," *Proc. Amer. Assoc. Adv. Sci.*, Vol. XXXIII (1885), pp. 428–32. (Philadelphia Meeting, September, 1884.)

ness of erosion in old age was likened to second childhood in the life of man.

The scheme as at present applied to an uninterrupted cycle involves, first, the initial stage (infancy), immediately following uplift and preceding marked erosional modification of the uplifted area. This stage is of theoretical value only since erosion is continuously active during uplift and a region is thus in youth before uplift ceases. In youth vigorous headward-working consequent streams begin to dissect and tear away the old surface. Youth is a stage of composite topography tending continually to more complete obliteration of the plateau areas. As a stage its duration represents an extremely small fraction of the total cycle length. With the disappearance of remnants of the old surface, a maximum of relief is attained and the region enters the mature stage. Streams are becoming subsequent in type. Maturity is characterized by rugged and varied topography.

As relief is reduced and the streams, now mainly subsequent, become more sluggish, the region, with no break in the continuity of denudation, passes into old age of the physiographic cycle. This stage is extremely long as compared with maturity as at present recognized. The subdued land surface occurring in a late fraction of this long stage has been designated "peneplain," "almost a plain." This term alone has been most valuable in carrying a definite physical concept and has been used widely in all geologic and geographic description. And, though peneplain has been considered the end-form of the erosion cycle, it is not truly so, since erosion-resisting residuals or monadnocks may occur. The theoretical ultimate end-form of the cycle of erosion is the plain, a surface with no prominent feature whatever.

The tremendously greater period of time required for carrying the cycle from maturity to late old age over that required from youth to maturity has led to a number of attempts to subdivide the later part of the cycle. Some, for example, have used the name of the surface form "peneplain," considered to characterize what is now generally regarded as advanced old age, to designate a new stage in referring to the "peneplain stage." Some confusion has arisen from the attempt to name surface forms in other stages of the cycle. It

seems particularly difficult in physiography to secure acceptable terms which will convey anything like the originally intended meaning to other workers. Despite this drawback it seems worth while to suggest a simple nomenclature correlating stage with surface form.

The youthful stage of the cycle does not involve much difficulty. The land surface with its plateaus and valleys is clearly a "youngland." A single term thus conveys the whole meaning and aspect of a region in youth.

The name "matureland" has been suggested by Bailey Willis[2] to denote an "eroded surface in a mature state of sculpture, qualified as vigorous, advanced, or subdued, according to the stage of development; a subdued matureland approaches a peneplain in flatness of relief." For the types designated as vigorous and advanced, matureland seems the logical word. The subdued type, however, would seem to carry matureland into the old-age stage, which is undesirable. Matureland should be applied to surfaces varying from those having attained maximum relief to those of reduced but *not low* relief.

The old-age stage, as at present understood, is by far the longest in the cycle, and the land forms characterizing its beginning and its end are quite different. The term "peneplain" is surely not applicable to the surface of early old age when relief of several hundred feet may exist. The stage, therefore, must be subdivided.

The writers suggest restriction of "old age" to that stage now regarded as early old age and characterized by subdued relief. The use of "oldland" to designate the land surface of old age in this restricted sense has been suggested.[3] Professor Davis, in an oral discussion, has objected to the use of this term because it is already in use to designate any ancient land. He suggested[4] the use of "senesland" instead. It seems to the writers that oldland is more suitable, because it is more self-explanatory and because it fits in better with the logical scheme of nomenclature suggested herein. The land

[2] "The Dead Sea Problem, Ramp vs. Rift," *Geol. Soc. Amer. Bull. 39* (1928), p. 493.

[3] John H. Maxson, "Geomorphic Features of Northwesternmost California," 30th Ann. Meeting, Cord. Sec., Geol. Soc. Amer. (1931).

[4] "Piedmont Benchlands and Primärrümpfe," *Geol. Soc. Amer. Bull. 43* (1932), p. 429.

surface of subdued relief whereon the streams are becoming sluggish is not only "senescent," or growing old, but is actually old in a physiographic sense.

The writers propose use of "senility" for late old age as it is now understood. Senility has been used as synonymous with old age as a stage term, but as in the case of human senility it is generally regarded as being related to very advanced old age. Such a breakdown in the physiographic-human analogy as is caused by introduction of a distinct stage beyond old age is due to fundamental difference in proportional distribution of time to stages. In human development the periods of youth, maturity, and old age are roughly equivalent, whereas of the physiographic cycle perhaps four-fifths is old age. The peneplain is the land surface characteristic of senility. Its average relief should not exceed one or two hundred feet, though an occasional monadnock might rise higher above the general level. The peneplain, though predominantly a cut surface, may be alluviated to varying degrees along stream courses and in areas closely approaching baselevel. The peneplain may be local or regional—in the former case being degraded over a limited though not a small area (e.g., of a few square miles); in the latter case being cut with respect to a very extensive baselevel (usually sea level). Two regional peneplains of different cycles and different average altitude may not exist adjacent to each other.

With respect to the total length of the erosion cycle, diastrophism is so continuously active in the earth's crust that deformation usually initiates a new cycle at least by the time senility is reached. Hence, in actual occurrence, the peneplain is the probable end-form. The ultimate theoretical land form attained is the plain, an expressionless land surface. On this surface stream activity is so impotent and surface modification so nearly arrested that the stage reached is essentially physiographic death!

THE ARID CYCLE

In consequence of field work in the southwestern United States, the writers have recognized some inadequacy in the nomenclature of desert surface forms. Terms used in connection with forms of the humid cycle are not fully applicable in arid regions, for, although the scheme of the erosion cycle with its progressive modification of

topography through youth, maturity, old age, and senility is universal in its validity, the relative importance of special agencies and special processes of erosion is definitely different in arid and humid climates; hence the land forms and their sequence in the two cycles are dissimilar. It is generally accepted that in arid regions mechanical weathering, wind erosion, torrential stream erosion, and sheetflood erosion are predominant, whereas chemical weathering and normal stream erosion are of principal importance in humid areas. Although in the following discussion primary consideration is given to a particular arid region, the Basin Range province, much of that which is said is applicable to the general case of the arid cycle. It is not intended to present a complete analysis but to review briefly the general concept of the arid cycle as developed by Davis,[5] Lawson,[6] and others, and to suggest a nomenclature useful in designating important surface forms of desert regions.

Nearly forty years ago the difference in agencies of erosion and the forms produced in the arid Southwest from those in a humid climate was observed by W J McGee,[7] who described sheetfloods and the pediments (piedmont rock-cut floors) that they assisted in producing in the Sonoran region. These features were observed subsequently by I. G. Ogilvie[8] and Sidney Paige.[9] But the significance of the phenomenon was generally overlooked until A. C. Lawson,[10] in an analytical study, showed that desert erosion in the Great Basin proceeds mainly not by broad reduction of mountainous uplands but by recession of faulted mountain fronts. In this recession a steep slope may be maintained throughout the existence of the mountain mass. Although differences of opinion exist as to the processes involved, that such a recession is a common mode of desert range reduction is confirmed by the work of Kirk Bryan[11] on pedi-

[5] "The Geographical Cycle in an Arid Climate," *Jour. Geol.*, Vol. XIII (1905), pp. 381–407.

[6] A. C. Lawson, "Epigene Profiles of the Desert," *Bull. Dept. Geol.*, Univ. Calif., Vol. IX (1915), pp. 23–48.

[7] "Sheetflood Erosion," *Bull. Geol. Soc. Amer.*, Vol. VIII (1897), pp. 87–112.

[8] "The High Altitude Conoplain, a Topographic Form Illustrated in the Ortez Mountains," *Amer. Geol.*, Vol. XXXVI (1905), pp. 27–34.

[9] "Rock-cut Surfaces in the Desert Ranges," *Jour. Geol.*, Vol. XX (1912), pp. 442–50.

[10] *Op. cit.*

[11] "Erosion and Sedimentation in the Papago Country, Arizona," *U.S. Geol. Surv. Bull. 730* (1923), pp. 19–40.

ments in the Papago country. It is likewise substantiated by the later work of Douglas Johnson[12] and William Morris Davis.[13]

Youth in the arid cycle of the Basin Ranges is initiated by the uplift of fault-block mountains, the summits of which will show the topography of the interrupted stage. Where earlier humid conditions prevailed, it may be an oldland or a peneplain; where earlier arid conditions prevailed, it may be a desert basin and ridge topography. The general processes of arid erosion will operate on the uplifted mass. In certain cases the summit areas may possess sufficient altitude to be subject to a humid climate, and this is a complication in the general Basin Range cycle. Since this discussion is intended to apply to the region as a whole rather than to the separate blocks which compose it, such complications will not receive attention here. The process of mountain-front retreat begins in youth and narrow pediments will be formed.

Physiographic youth in the arid cycle is characterized by maximum relief—in the Basin Range province originally produced by differences in elevation of the uplifted and depressed blocks—and by the dominance of independent drainage basins, forming local baselevels. The characteristic topography is of the basin and range type; this will be the case whether faulted or folded structures are predominant. A surface of this type, exemplified today in the Death Valley–Panamint Valley region of California, may properly be called an "arid youngland."

Maturity in the arid cycle is characterized by a reduction in relief, which may be accomplished partly by a lowering of the mountains and partly by a filling of basins with alluvial material, and by a progressive integration of drainage basins. The lowland areas are enlarged at the expense of the highlands—in part, at least, as Lawson has demonstrated, by the retreat of the mountain front. Long piedmont slopes flank the mountain blocks; the canyons broaden in their lower reaches; the mountain fronts lose their sharpness and regularity. Such a surface, which may now be observed in the Papago country of Arizona, may be termed an "arid matureland."

The recession of front and reduction of mountain mass proceeds

[12] "Rock Planes of Arid Regions," *Geog. Rev.*, Vol. XXII (1932), pp. 656–65.

[13] "Granitic Domes of the Mohave Desert," *Trans. San Diego Soc. Nat. Hist.*, Vol. VII (1933), pp. 211–58.

until only narrow ridges and "inselberge" are left, surrounded on all sides by rock-cut floors which in turn are overlapped by alluvial deposits covering earlier-cut portions of the floor and the intermont basins. Widely extending rock-cut and alluviated surfaces of this type formed by the coalescence of a number of pediments and occasional desert domes may be called "pediplains." The pediplain usually forms the largest part of the old-age surface. In this stage of the cycle, integration of drainage has become complete and the entire region has a common baselevel. Wind has increased in importance as an agent of erosion. Since faulting or folding may not have initiated the cycle uniformly and differences in resistance to erosion of rocks comprising the ranges may exist, comparable reduction of all ranges is not to be expected. When the surface consists for the most part, however, of narrow ridges and pediplains, the region may be considered to have reached old age, and its characteristic surface may be called an "arid oldland."

In the senile stage of the cycle disintegration of the drainage begins and becomes more strongly emphasized toward its conclusion. In more completely arid regions wind is the dominant agent of erosion. The structural basins have been filled with waste; the mountains have disappeared and desert domes mark their former position. In discussing desert surfaces of this stage Eliot Blackwelder[14] stated:

> Pediments are essentially compound graded flood plains excavated by ephemeral streams. As their growth corrodes the mountain mass, they may eventually coalesce to form smooth graded domes to which Lawson applied the term "panfan" (meaning "all fan")—a name that is etymologically unfortunate because these features are not concerned with alluvial fans at all. Of such a dome the best illustration that has been cited is the broad granite dome near Cima [Footnote: W. M. Davis, "The Basin Range Problem," *Proc. Natl. Acad. Sci.*, Vol. XI (1915), pp. 389–92; D. F. Hewett, unpublished report and geologic map showing that the panfan is underlain almost entirely by granite.] in southeastern California. The panfan is in fact the desert-inhabiting species of the genus peneplain—if a geologist may borrow the terminology of the biologist—and the higher gradient which distinguishes it is conditioned by aridity.

The "desert dome" as defined by Davis[15] is merely a single feature of the desert surface on the summit area of which bedrock is exposed

[14] "Desert Plains," *Jour. Geol.*, Vol. XXXIX (1931), p. 138.

[15] "Granitic Domes of the Mohave Desert," *op. cit.*, p. 227.

through action of "rock-floor robbing by sheetfloods." Because of the importance of rock-floors the term "panfan," originally intended to apply to the regional surface and not to individual domes, seems inappropriate and a new term is needed.

A reduced desert surface, because of its low relief, has not only suggested Blackwelder's correlation of "panfan" and peneplain, but has led to rather general designation of such surfaces as actual peneplains. This usage does violence to the concept of peneplain, since this surface originates after prolonged regional downcutting through the definite form sequences of youth, maturity, and old age. Although the two surfaces may often closely resemble each other and may, indeed, occasionally be difficult to tell apart, especially if partially dissected, they have passed through an entirely different development and usually possess distinguishing characteristics. The senile desert surface is, therefore, not entitled to the term "peneplain." Moreover, as Bryan[16] has stated:

> . . . . under conditions of extreme aridity the development of plains cut on rock does not necessarily indicate old age, but such plains may be produced earlier in the cycle and are dependent for their production on the upper limit of alluvial deposition in the intermontane valleys.

The new term should apply to the surface of low relief formed by widespread coalescence of rock-cut desert domes considered in conjunction with their surrounding shallow alluviated depressions. Since the penultimate broadly undulating surface is composed of exposed summits of rock domes and radiating alluvial fans, it may suitably be called a "fandomeplain." Though the length of time required to produce a fandomeplain may not be so long as that required for the development of a peneplain, their positions in their respective cycles are similar. The fandomeplain is characteristic of senility in the arid cycle of the Basin-Range province.

It should be emphasized here that the fandomeplain is partly rock-cut and partly filled, and that as the development of the cycle proceeds into late senility the alluviated part tends to decrease, the wind being the most effective agent of removal of waste. The ultimate surface form of the arid cycle may then be a true erosional plain with little or no alluvium. In some places wind erosion may be

[16] *Op. cit.*, p. 54.

so active as to excavate new basins in weaker rocks. This development of relief contrasts with the lack of relief continuing through the terminal stage of the humid cycle. For the plain, resembling in varying degree the true plain of the humid cycle, but differing from it in origin, the name "ariplain" is suggested.

It should be indicated that the formation of the fandomeplain is about as improbable in actual production as the degradational plain of the humid cycle because of the relative crustal instability of the Great Basin area. Surfaces characteristic of earlier stages, however, should occur commonly. The writers believe that a large part of the Mohave Desert of southeastern California, and especially the eastern portion, is an arid oldland in the sense defined in this paper. The alluvium of the eastern part, the Mohave River drainage area, is being removed to lower basins. The wind is an effective agent in this transportation. An uplifted and dissected pediment in the northern Inyo Range which has been studied by the writers[17] is regarded as a portion of a widespread pediplain. Pleistocene and recent upfaulting has led to the initial stage of a new cycle.

The nomenclature for cycles in arid and humid regions may be indicated tabularly:

Stage	Humid Cycle	Arid Cycle
Youth	Youngland	Arid Youngland
Maturity	Matureland	Arid Matureland
Old Age	Oldland	Arid Oldland
Senility	Peneplain	Fandomeplain
End	Plain	Ariplain

Acknowledgments.—In conclusion the writers wish to acknowledge their indebtedness to Dr. J. P. Buwalda, of the Division of Geology and Paleontology at the California Institute of Technology, for advice and suggestions in the writing of this paper and to thank him for critically reading the manuscript.

[17] "Physiography of the Northern Inyo Range," 33rd Ann. Meeting, Cord. Sec., Geol. Soc. Amer., Berkeley, California (1934).

VENTIFACT LOCALITIES IN THE UNITED STATES

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ABSTRACT

Information is presented concerning sixty-one ventifact localities in nineteen states, of which eight yield specimens believed to be of pre-Pleistocene origin. Southeastern Massachusetts, southern California, and Wyoming are the chief regions where ventifacts occur.

In 1930 the senior author, impressed by the sporadic and little-known occurrence of sandblasted pebbles, circulated a questionnaire seeking information on localities, conditions of formation, abundance, sizes, and the like. After a considerable number of replies had been received, the junior author undertook the compilation and analysis of results. At that time it was thought that to the compilation might be added a general summary of information on ventifacts with reference to foreign localities and that certain experimental work might be undertaken and reported.

Since that time, however, Bryan has published an extensive bibliography with notes on various papers,[1] Schoewe has presented the results of experimental studies,[2] and Matthes has discussed the formation of these carved stones and their relation to glacial history in Massachusetts.[3] Because of these studies and the necessary turning of attention to other matters, it remains only for the present writers to present the list of localities with brief notes on the conditions of formation and characteristics of the ventifacts as reported in replies to the questionnaires.

In all, 50 individuals replied to the questionnaire, 39 sending some

[1] Kirk Bryan, "Wind-Worn Stones or Ventifacts—A Discussion and Bibliography," *Nat. Res. Council, Reprint and Circular Ser. No. 98* (1931).

[2] W. H. Schoewe, "Experiments on the Formation of Wind-Faceted Pebbles," *Amer. Jour. Sci.*, Vol. XXIV (1932), pp. 111–34.

[3] F. E. Matthes, "Wind-Faceted Pebbles from the Glacial Drift of Nantucket," *Proc. Geol. Soc. Wash., Jour. Wash. Acad. Sci.*, Vol. XXIV, No. 4 (1934), pp. 195–96.

information on localities. In addition the questionnaire reached 59 other geologists whose names were checked off in the U.S. Geological Survey office. These either had no information to offer or felt that their recollection of localities was of little value or would be duplicated by others. Probably in a number of universities those receiving questionnaires conferred with colleagues or students, so it is probable that some 200 or 250 people were reached indirectly. The sporadic and somewhat rare occurrence of ventifacts is emphasized by the fact that a number of geologists of wide experience reported that they had never seen one of these in the field and this is doubtless true of many of those who failed to reply at all. The gratifying number of useful returns and the representative listing of localities is largely due to the cordial assistance of Dr. W. H. Bradley, who was responsible for circulating the questionnaire forms among geologists of the U.S. Geological Survey. It is hardly to be expected that such a compilation will be complete, but it is believed that the chief districts of ventifact occurrence have been outlined and localities indicated in several parts of the country, from which collections can readily be made. Naturally certain major districts of occurrence consist of many specific localities, described differently by individual observers. Where there is clear identity of localities reported by two observers, only one notation is made, otherwise two or more references to localities in the same general area are both presented (Table I).

TABLE I

LOCALITIES WHERE VENTIFACTS HAVE BEEN FOUND[4]

ARIZONA

1. Near Tucson

CALIFORNIA

2. Near Palm Springs station
3. Ivanpah and Mesquite valleys, Ivanpah quadrangle
4. San Gorgonio Pass, Southern Pacific Railroad, east of Garnet station
5. Between Lone Pine and Independence, Inyo County
6. Near McLean Spring, central Death Valley

[4] Because of the authors' unfamiliarity with many of these localities and various phraseology used by observers in descriptions, there are probably several duplications in this table, as well as indication of two or more specific places in several general districts.

COLORADO

7. Table Mesa, north of Boulder
8. Near Lyons
9. 4 miles northeast of Boulder, east of Valmont
10. 3 miles north, 6 miles east of Boulder (White Rocks)
11. Near Colorado Springs

IDAHO

12. South of Pocatello, to Utah line

IOWA

13. Pebble band Iowan till, various localities

MAINE

14. Bethel and West Bethel

MASSACHUSETTS

15. Near Oak Bluff, Marthas Vineyard
16. Cape Cod
17. Bluffs at Highland Light, Cape Cod
18. Ocean side of Cap Cod
19. Marthas Vineyard
20. Nantucket
21. Ipswich Beach

MICHIGAN

22. Betsie Point, Benzie County
23. Sleeping Bear Point, Ledanau County
24. Near Grand Marias, Alger County
25. Near Foster, northern Michigan
26. Head Little Traverse Bay, 4 miles north of Petoskey

MISSOURI

27. Short distance west of St. Louis

MONTANA

28. Various places on gravel benches and terraces
29. 5 miles east of Springdale, Sweetgrass County

NEBRASKA

30. North bluff of Platte River one mile east of Ogallala

NEVADA

31. Clarke County
32. One and one-half miles north of head of Black Canyon, near Las Vegas

NEW JERSEY

33. Highway crossing of Pennsylvania Railroad, southwest of Princeton Junction
34. Hammonton, Camden County
35. East of Woodbury, Camden County
36. Princeton Junction

NEW YORK

37. Wind-eroded kames, northern New York
38. Near Rochester

NORTH CAROLINA

39. Triassic localities

TEXAS

40. Ranger district
41. Hueco Mountains, west Texas

UTAH

42. Near Pinto Farms, San Juan River
43. 25–40 miles south of Greenriver, Green River desert

WISCONSIN

44. Chippewa Falls
45. North and southeast sides of Baraboo range, west of Ablemans
46. Hamilton Mounds, Adams County
47. West of Baraboo, south of Ablemans

WYOMING

48. Moorcroft, Newcastle and Devils Tower quadrangles
49. T. 29 N, R 86 W, near west end Pathfinder reservation, west of Alcova
50. Wagon Mound bench, Cottonwood Creek, Hot Springs County
51. Between Riverton and Shoshone
52. Along Highway 87 southeast of Dubois
53. Along Highway 187, northwest of Farson, 10–20 miles
54. Ten miles southwest of Shoshone, highway to Lander
55. Various points 5–10 miles south of South Pass
56. Two-hundred-foot terrace on Clark Fork 2 miles south of Montana line
57. Wind River basin, 40 miles northwest of Riverton
58. Base of Medicine Bow Mountains from Centennial to Elk Mountain post office
59. Crest of Laramie Range at crossing U.S. Highway 30
60. Just west of Cody
61. Park and Hot Springs counties

Descriptions of most of the localities listed show why sandblasting action is prominent, but it remains rather difficult to explain why ventifacts are not found at many more places, where conditions for sandblasting seem equally favorable. Apparently a long-maintained stability of surface and constancy of conditions are of great importance, these in some instances being related to a prominent physiographic feature such as a shoreline or a windgap. So many observers have here, or elsewhere, mentioned the relationship of sandblasting to morainic or ice margin situations that this factor must be significant.[5] Apparently high local wind velocities, combined with the abundance of loose, detrital material and lack of vegetation has led to exceptionally effective eolian abrasion immediately following retreat of glacial ice from various areas.

Localities at which the ventifacts are derived from formations not of recent origin are listed in Table II.

Localities where the sandblasting action appears to be at least in part modern fall into several general classes. Practically all are either along a shore (21, 24, 26), in arid or semi-arid localities, like many of the western localities, or at points where rock fragments were subject to exceptional sandblasting during or soon after glacial times (13, 16, 17, 23, 29, 35, 37, 38, 52). Many are on the surfaces or margins of terraces or mesas where pebbles are exposed to strong, persistent winds from adjacent areas of lower elevation (4, 6, 7, 28, 29, 32, 42, 48, 50, 51, 54, 57, 58, 60).

Estimates of abundance of various varieties indicate that there are only a few localities at which considerable numbers of well-characterized dreikanter, einkanter, or other carved shapes could be found in a short time. Nearly every one of these localities was mentioned by more than one observer and there was general agreement as to abundance. These included several of the localities of Wyoming (51, 55, 58, 61), one each in Texas (40), Utah (43), and Nevada (31). The two most-mentioned localities in point of abundance of mature forms were Highland Light, Cape Cod, and San Gorgonio Pass, California. Fairly good collecting was indicated at some other California and Massachusetts localities.

[5] E. Blackwelder, "Sandblast Action in Relation to the Glaciers of the Sierra Nevada," *Jour. Geol.*, Vol. XXXVII (1929), pp. 256–60.

As would be expected, many of the localities were chiefly marked by rock fragments showing pitted or polished surfaces, with only an occasional fragment showing clear evidence of carving or the development of sharp edges by wind abrasion. The abundance of sand

TABLE II

LOCALITIES FOR FOSSIL VENTIFACTS

Locality No.	Geologic Age	Source of Ventifacts
44	Upper Cambrian	Basal Mt. Simon sandstone, in contact with pre-Cambrian.
25	Cambrian-Ozarkian contact	Top of Jordan sandstone, base of Devils Lake sandstone.
45	Cambrian-Ozarkian contact	Base of Devils Lake sandstone.
33	Triassic	Basal conglomerate of Stockton formation.
39	Triassic	Triassic conglomerate.
43	Jurassic	In upper 10 feet of Navajo sandstone.
27	Tertiary (?)	Gravel at top of Pennsylvanian.
55	Tertiary	Old erosion surface crossing Tertiary or early Pleistocene.
13	Pleistocene (post-Iowan)	From pebble band on Iowan till.
23	Pleistocene (Nipissing or post-Nipissing)	From Nipissing or post-Nipissing beach.
15–21, incl.	Pleistocene (in part)?	From glacial deposits, carving probably most active during close proximity of the ice.
29	Pleistocene (in part)?	Pleistocene terrace surface, carving in glacial time.
37	Pleistocene (in part)?	Pleistocene kame gravel, carving in glacial time suspected.
38	Pleistocene (in part)?	Same.
47	Pleistocene (in part)?	Glacial boulders, carved by sand from glacial lake shore during glacial time (?).
52	Pleistocene (in part)?	Pleistocene moraine materials, carving apparently more active formerly than now.

is doubtless an important factor. The senior author has noted in various more arid parts of the Hawaiian Islands, but especially in the desert strip of Molokai, evidence of strong wind grooving of weathered rock and soil and some shaping of rock fragments. The conclusion was reached, however, that the lack of quartz or any other hard mineral in the sand was a very serious handicap to the

wind in producing strongly carved pebbles. The tendency of the soft calcareous sand is rather to cut away only softer parts of weathered surfaces. It is believed that here, with the remarkable persistence of the trade winds, were quartz grains present, some very striking pebble carving would result.[6]

A number of observers mention the high polish produced by sandblast action (4, 7, 8, 9, 10, 26, 29, 30, 48, 55) and several point out that lack of polish at certain localities is due to softness of the rocks.

Sizes of ventifacts at various localities are largely determined by sizes of available rock fragments, these in turn due to the agent—glacier, stream, or waves—which placed them. Nevertheless certain limitations in size are discernible. Most of those replying to the questionnaire mention as minimum sizes "half-inch," "quarter-inch," "walnut size," or the like. One reported "from sand-grain size up," but the majority recognized a minimum size somewhat larger than the smallest pebbles. Observations by the senior author at localities 29, 52, 53, and 55 suggested that with winds of sufficient velocity to sandblast effectively, only pebbles of sizes in excess of one-half inch were sufficiently stable to be carved to distinctive shapes. Slight variations in the limit due to this factor would be expected from place to place.

According to several observers the larger boulders and blocks were fluted, grooved, or perhaps only polished and pitted, but the most characteristic einkanter or dreikanter were limited in size to a few inches, 5, 6, or 8, in various replies. At some of the localities mentioned in the preceding paragraph very striking einkanters up to 15 inches long were found, and well-marked dreikanters of slightly less dimensions. It is apparent that the formation of a large dreikanter wholly by carving involves cutting to greater depths than in the formation of a moderate sized one, and must in general be much less common. On the other hand, an occasional large rock fragment having a somewhat favorable initial form may have its sides so dressed and edges so sharpened as to become a very striking einkanter or dreikanter.

[6] C. K. Wentworth, "Desert Strip of West Molokai," *Univ. Iowa Studies in Natural History*, Vol. XI, No. 4 (1925), pp. 50–51.

One very large ventifact with sharply cut edges and minutely fluted surface, over 2 feet long, was seen at locality 55. This was so striking that a friend of the writers later made a visit to the spot, with full equipment for loading a valuable museum piece into the car. It was with no little distress that the expedition returned empty handed, the specimen having strangely disappeared from the side of the little-traveled road in the meantime. It is only to be hoped that this substantial monument to the potency of the wind was found by some other public-spirited geologist and has been placed on exhibit in a suitable setting.

REVIEWS

Beiträge zur Untersuchung der isostatischen Kompensation der schweizerischen Gebirgsmassen. By MARIETTE LEHNER. "Verhandlungen der Naturforschenden Gesellschaft in Basel," Vol. XLI. Pp. 76; figs. 19; pls. 2.

An attempt is made by Miss Lehner to apply the test of observation and calculation to the question of local versus regional isostatic compensation. Her work is an outgrowth of the work of Niethammer, references to which will be found at the end of the article. The whole investigation is summed up by Niethammer in the report of Swiss Geodetic Commission to International Association of Geodesy for its Lisbon meeting (*Travaux de l'Association Internationale de Géodésie*, Vol. XI [Paris, 1933]).

Switzerland offers many advantages for an observational test of the question of local versus regional isostasy, for the topography is rugged and the number of gravity stations large. The test was made by computing isostatic reductions, using the actual detailed local topography for deriving the topographic effect, but a topography generalized in varying degree for deriving the effect of the compensation. The distinction between the actual and the generalized topography was made only for the area within 188 kilometers of the station. At a greater distance the distinction is unnecessary because of the size of the compartments used in reading the topographic maps.

The topography was generalized by drawing contours, not from the actual elevations but from the mean elevations within squares of certain sizes, namely, with sides 8, 64, and 128 kilometers in length. The generalized contours based on the 8-kilometer squares still show many traces of local topography. On the map based on the 64-kilometer squares the high Alps in the region of Mont Blanc and Monte Rosa are shown by the presence of a 2,200-meter contour, but the valleys of the Rhone and Rhine in Switzerland are wiped out and the Jura Mountains merge gradually into the Alps. The Black Forest, the Vosges Mountains, the Rhone-Saône region in France, and the plain of the Po are, however, still in evidence. On the map based on the 128-kilometer squares the Jura, the Vosges, and the Black Forest disappear; but the Rhone-Saône region, the plain of the Po, and the Apennines are still traceable.

For each of these three degrees of generalized topography isostatic anomalies were computed for four depths—80, 100, 120, and 140 kilometers—giving in all, $3 \times 4 = 12$ sets of gravity anomalies. All computations were made, for convenience, with the Pratt type of compensation. A constant correction, x, was determined for each set in such a way that the mean anomaly became zero. This correction includes a correction to the value of theoretical gravity used in deriving the anomalies, a correction that may be treated as constant over the limited range of latitude.

The criterion adopted to decide on the most probable hypothesis was that the mean anomaly (or, more accurately, the "root-mean-square") should be a minimum. The absolute minimum seemed to lie outside the range of computed conditions. Extrapolation gave the following approximate results for the number of gravity stations used, namely, 363.

T = Depth of compensation = 60 km.
A = Side of square = 8 km.
μ = Root-mean-square anomaly = 18.2 milligals
x = Constant correction = -30 milligals

These results seemed rather improbable, especially the large constant correction and the small size of the square, which latter would imply almost absolutely local compensation. Accordingly, the preferred results for the whole 363 stations were taken as—

T = Depth of compensation = 80 km.
A = Side of square = 8 km.
μ = Root-mean-square anomaly = 18.7 milligals
x = Constant correction = -20 milligals

There was both a mathematical and a physical reason for questioning these results. The mathematical reason was the form of the curve representing the frequency of accidental error to be expected if no systematic disturbance were present, but the curve of frequency found was not of this sort. The physical reason is that geologists suspect that both the northern and the southern parts of the region considered, namely, the vicinity of Basel and part of the Jura region in the north and part of Ticino in the south, are not in isostatic equilibrium. Stations in these regions were therefore excluded. The criterion used was necessarily somewhat arbitrary; it was based on the size of the Bouguer anomaly. When the number of stations was reduced to 274, the curve of frequencies was not greatly improved, and a further reduction to 191 was tried; the additional stations excluded were mostly in the north. The curve of frequencies was greatly improved, though it is still not absolutely the curve of

frequency of accidental error. The results from the 191 stations in Central Switzerland are:

T = Depth of compensation = 100 km.
A = Side of square = 64 km.
μ = Root-mean-square anomaly = 11.5 milligals
x = Constant correction = 0 milligals

The result of the investigation may be summed up by the statement of Niethammer, that in the central portion of the Swiss Alps the observed values of gravity may be represented, with an average root-mean-square anomaly of 11.5 milligals—that is, with a "probable" anomaly of 8 milligals—by regional compensation of the Pratt type to a depth of 100 kilometers, the region in independent equilibrium having an area of at least 64^2 square kilometers, or about 4,000 square kilometers.

It might seem illogical to argue about the depth of compensation for stations close to regions where isostatic compensation is supposed to be imperfect or absent. In the present instance there is a rough-and-ready way out of the difficulty that justifies the procedure actually adopted. Stations in the regions to the north and south of Central Switzerland are affected by the lack of compensation and in varying amounts, so that they are properly omitted from the discussion. Stations in Central Switzerland are, of course, also affected but the amount is more nearly constant. This is because the uncompensated regions lie on both sides of the central portion and because, if we move toward one such region, we move away from the other. This roughly constant effect is taken care of by the correction x, which in the present investigation is merely a mathematical convenience. So many causes contribute to the value of x that their sum total has no geophysical significance and there are no data for analyzing x into its component parts, which alone would be significant.

WALTER D. LAMBERT

Tertiary Faunas. By A. MORLEY DAVIES. London: Thomas Murby & Co. (1934). Pp. 250; figs. 28; pl. 1. 15*s*.

Tertiary Faunas, by A. Morley Davies, fills the great need for an up-to-date summary of the most important data pertaining to the Tertiary deposits of the world. Professor Davies has long been interested in the problems of Tertiary correlation, and in his book one may find the latest ideas as to correlation, together with a number of new paleogeographic maps which show the local distribution of the deposits of the different epochs.

Some of the principal problems of ecology and their relationship to

paleontology are discussed in the first chapter under the heading "Geographic Distribution of Animal Life." The following are some of the subjects covered in the second chapter under the heading "The Geological Interpretations of Fossils": facies, fossils and zone-fossils, lineages and persistent species, cycles of sedimentation, Lyell's percentage classification, and subdivisions of the Cainozoic era. These two chapters, though brief considering the fields they cover, give a good general statement of the problems involved, and the well-chosen Bibliography at the end of each contains some of the principal references on those subjects.

Chapters iii and iv give a general résumé of the distribution and general characters of the deposits and faunas of the Tertiary. Chapter iii begins with a brief review of some of the principal facts concerning the relationship of the invertebrate faunas of the Upper Cretaceous to those of the Lower Tertiary. In treating of the different divisions of the Tertiary, Professor Davies discusses in detail the generic and specific relationships that exist between the marine invertebrate faunas of the numerous provinces. He also gives a short review of the distribution and relationships of the different Tertiary vertebrate faunas.

Appended to the book are ten correlation tables which cover all the chief known Tertiary areas of the earth. The bibliographies following chapters iii and iv contain references to the most important literature of the Tertiary and will be very valuable to the geologist or paleontologist studying a new region, or to the student who wishes to become acquainted with the literature of the Tertiary of the world.

BRUCE L. CLARK

Der geologische Aufbau der Erde. By A. BORN. *Handbuch der Geophysik*, Vol. II, Lieferung 2. Berlin: Bornträger, 1932. Pp. vi+565–876. Illustrated. Rm. 55.20.

The book is a regional geology of the world based on structural facts. Only that portion of the earth's crust which can be geologically examined is considered. Theories of continental and oceanic evolution are dismissed with a short reference to the works of R. Staub and L. Kober. The absence of an Index is a handicap in the use of a volume which treats such a very large subject. In spite of the fact that 221 illustrations are included, the use of an atlas with rather detailed maps of different countries is necessary. The style is very compact, and an enormous amount of information is conveyed to the reader. The book is extremely instructive, especially as an introduction to structural and regional geology.

A. C. NOÉ

Über Werden und Zerfall von Kontinentalschollen. By A. BORN. "Fortschritte der Geologie und Palaeontologie," Vol. X, Heft 32. Berlin: Bornträger, 1933. Pp. 347–422. Rm. 10.

The author tries to organize all available data for an explanation of the building and breaking-up of continental masses. He admits the existence of continental horizontal drift in a limited number of cases. Much more important seem to him the vertical movements of great blocks. Through this type of movement, important changes are produced in the composition of continents.

A. C. NOÉ

Das Ruhrgebiet. By HANS SPETHMANN. Vols. I and II. Berlin: R. Hobbing, 1933. Pp. 676; figs. 192.

One of the greatest coal fields and industrial districts of Europe is described from an economic point of view, giving its development from the time of its first alien invasion under the Roman emperor, Tiberius, to the occupation by the French, which ended in 1925. The book is richly illustrated and shows the intricate connection between mineral resources, industries, and topographic development. The material is of equal interest to the economic geologist and geographer. A third volume is promised.

A. C. NOÉ

Deecke-Festschrift. By WILHELM DEECKE, gewidmet von Schülern und Freunden. "Fortschritte der Geologie und Palaeontologie," Vol. XI. Berlin: Bornträger, 1932. Pp. xxvi+532. Illustrated. Rm. 44.

In 1932 Professor W. Deecke, who was Professor of Geology in Freiburg and for seventeen years Director of the Geological Survey of Baden, celebrated his seventieth birthday and twenty-four friends and former students contributed to a volume including a variety of fields: vulcanism, geophysics, economic geology, sedimentation, stratigraphy, paleontology, structural geology, glaciation, and regional geology of the German state of Baden. A few of the many well-known names appearing among the authors are those of S. von Bubnoff, H. Cloos, H. Schneiderhöhn, M. Pfannenstiel, A. Born, and W. Soergel.

A Bibliography of Deecke's publications from 1881 to 1931 follows the dedication chapter and from it can be learned how immensely broad Deecke's interests must have been, since he published books and papers in almost every subdivision of geology and paleontology. He belongs to a

generation of scientists who specialized much less than is customary at present and who produced much more, because of, or in spite of, that fact.

A. C. Noé

The Geology and Ore Deposits of Sierra County, New Mexico. By G. T. Harley. State Bureau of Mines and Mineral Resources Bull. 10. Socorro, 1934. Pp. 220; figs. 19; pls. 11; maps 2. $0.60.

Sierra County, one of the chief mining counties of the state, has produced silver and gold valued at approximately $21,000,000. The period of greatest mining activity was from 1877 to 1901. Because of the recent rise in the price of gold, interest in the ore deposits of the county has increased greatly, and mining and prospecting have had a marked revival.

This bulletin treats of the geology and mineralogy of the region, together with the history of the various mines, their production and future possibilities.

R. T. C.

Historical Geology. By Walter A. Ver Wiebe. 1934. Pp. 162; figs. 205.

Historical Geology is a concise account of the geology of North America, with comments on that of other continents. The author, departing from the usual order of presentation, begins his discussion with the Quaternary and concludes it with the pre-Cambrian, in order to proceed from "the known to the unknown." Paleogeography has been stressed in an attempt to give the student a broad conception of conditions at selected times and to enable him to grasp more readily the stratigraphy of the various sections of the continent.

Geological theories are taken up in conjunction with the discussions of the periods which best illustrate them. To complete the history, an ample summary of the paleontology of each geological division is given at the end of each chapter. The text is supplemented by many well-chosen illustrations, including paleogeographic maps, topographic maps, cross sections, and correlation tables.

E. C. Olson

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